Disertační práce

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Metodika hodnocení rizika pádu pomocí kvantitativní analýzy signálů

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Poděkování

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Prohlášení

Prohlašuji, že jsem předloženou práci s názvem *Metodika hodnocení rizika pádu pomocí kvantitativní analýzy signálů* vypracovala samostatně a že jsem uvedla veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze, 16. August 2020

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Slávka Neťuková

Anotace

S rostoucím věkem u seniorů dochází častěji k pádům. Běžně používanou metodou určování rizika pádu je test Timed Up & Go (TUG), u kterého je hodnocen čas, za který subjekt vstane ze židle, ujde rovně 3 metry, otočí se, jde zpět k židli a opět na ni usedne. Současně s rychlým rozvojem nositelných technologií dochází k nárůstu jejich využívání při analýze pohybu lidí, včetně hodnocení rizika pádu a testu TUG. Cílem disertační práce je analýza testu TUG snímaného inerciálními senzory a tlakocitlivým chodníkem. Toho bylo docíleno segmentací signálů testu TUG na jednotlivé komponenty (sed-do-stoje, chůze před otáčením, otáčení, chůze po otáčení, stoj-do-sedu) a jejich následným rozborem. Konkrétně, u komponenty sed-do-stoje byla provedena analýza jejího rozdělení na pod-fáze a rozbor vhodnosti jednotlivých signálů inerciálních senzorů pro kvantifikaci. U chůzových komponent byla provedena analýza opakovatelnosti chůzových parametrů a analýza samostatného hodnocení chůzových komponent před a po otáčení. Pro komponentu otáčení byl proveden rozbor signálů inerciálních senzorů, a dále byl navržen nový parametr pro hodnocení otáčení.

Klíčová slova: analýza pohybu, Timed Up & Go, inerciální senzor, tlakocitlivý chodník

Školitel: doc. Ing. Zoltán Szabó, PhD.

Annotation

With increasing age, seniors are more likely to fall. The commonly used method of determining the risk of falling is the Timed Up & Go (TUG) test. TUG evaluates the time it takes for the subject to get up from the chair, walk 3 meters, turn around, go back to the chair and sit on it again. Simultaneously with the rapid development of wearable technologies, there is an increase in their use in the analysis of human movement, including the assessment of the risk of falls and the TUG test. The aim of the dissertation is to analyze the TUG test sensed by inertial sensors and a pressure-sensitive walkway. This was achieved by segmenting the TUG test signals into individual components (sit-to-stand, walk before turn, turn, walk after turn, stand-to-sit) and their subsequent analysis. Specifically, the efectivness of dividing sit-to-stand component into sub-phases was analyzed. Suitability of individual inertial sensor signals for quantification for furher processing and analysis. For walking components, an analysis of the repeatability of gait parameters and an analyses of a separate evaluation of walking components before and after turn were performed. An analysis of the signals of inertial sensors was performed for the turn component, and a new parameter for the evaluation of turn was proposed.

Keywords: movement analysis, Timed Up & Go, inertial sensor, pressure sensitive walkway

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Kapitola 1

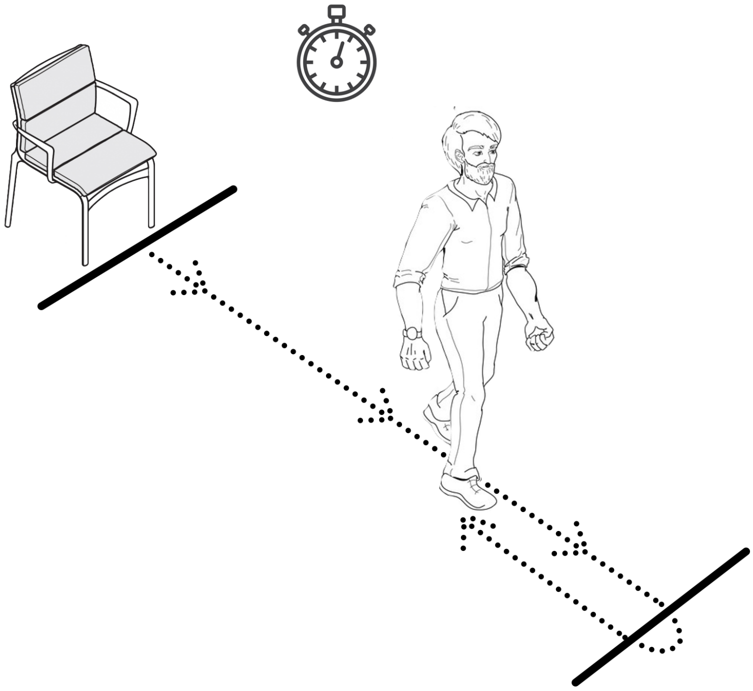
Úvod

S rostoucím věkem u seniorů dochází častěji k pádům. To je způsobeno různými faktory, včetně problémů s rovnováhou, špatným zrakem či demencí. Přibližně třetina lidí věku starších 65 let žijících doma spadne nejméně jednou ročně. Následkem některých pádů jsou fraktury a nutnost lékařského ošetření. Časté bývají také obavy z pádu. Vlivem těchto obav senioři omezují své pohybové aktivity a to může dále snížit jejich nezávislost a také kvalitu života [1]. Opakované pády jsou hlavním důvodem, pro který jsou senioři přijati do nemocnice [2, 3]. Z výše zmíněných důvodů jsou pády považovány za důležitý problém veřejného zdraví a je věnován zesílený zájem nalezení způsobů včasné identifikace vyššího rizika pádu, jejich prevence a omezení jejich negativního dopadu na jednotlivce i společnost jako celek.

Existuje řada metod pro hodnocení mobility se zaměřením na rovnováhu, chůzi a pohyby podílející se na běžných denních činnostech. Příkladem je STRATIFY (St. Thomas Risk Assessment Tool in Falling elderly inpatients). Tato metoda obsahuje 5 položek (historie pádů, rozrušenost pacienta, zrakové postižení, potřebu častého vyprazdňování, úroveň mobility), z nichž je každá bodovaná. Riziko pádu je pak hodnoceno na základě celkového počtu bodů, kterými byl pacient skórován.

Dalším běžně používanou screeningovou metodou je test Timed Up & Go (TUG) (obrázek 1.1). Test TUG byl odvozen z testu Get up and Go [4]. Při provádění testu TUG je měřen čas, za který pacient vstane ze židle, ujde pohodlným a bezpečným tempem vzdálenost 3 m, otočí se, vrátí se zpět k židli a usedne. Riziko pádu je určeno na základě času, který pacient potřeboval k vykonání testu.

American Geriatric Society and the British Geriatric Society (USA, GB) doporučuje test TUG jako rutinní screening pro hodnocení rizika pádu [5]. National Institute of Clinical Evidence (UK) se rovněž zasazuje o používání testu TUG jako metody pro hodnocení chůze a rovnováhy při prevenci pádů



Obrázek 1.1: Schéma testu Timed Up & Go.

u seniorů [6].

Kromě standardního testu TUG existují i jeho delší varianty na 7, 10 metrů či varianty rozšiřující provádění testu za současného plnění dalšího úkolu. Jedná se o kognitivní test TUG a manuální test TUG. Při kognitivní variantě plní pacient během provádění testu ještě i kognitivní úlohu. Kognitivní úlohou bývá například opakované odečítání čísla 3 či 7 od počátečního čísla 100. Při vykonávání manuální varianty nese pacient v ruce sklenici s vodou.

Současně s vývojem technologií, převážně nositelných technologií, došlo i k rozšíření jejich využívání v analýze pohybu. Zaměříme-li se pouze na test TUG, je umístění inerciálních měřících jednotek na tělo subjektu nejčastější variantou. Dalšími používanými prostředky jsou kamerové systémy [7, 8] a smartphones [9]. Test TUG, jehož hodnocení je rozšířeno moderními technologiemi, bývá v literatuře označován jako přístrojový (v angl. originále instrumented) nebo kvantifikovaný (v angl. originále quantified) test TUG. Před rozšířením a zavedením přístrojového testu TUG do výzkumné či klinické praxe je důležité podrobit jej zkoumání.

Hlavním zaměřením této disertační práce je analýza testu Timed Up & Go, což obsahuje rozbor signálů inerciálních senzorů, analýza opakovatelnosti chůzových parametrů při opakovaném měření, a srovnání chůzových parametrů před otáčením a po otáčení. Cíle práce, které úzce navazují na poznatky uvedené v kapitole 2 Současný stav řešené problematiky, jsou definovány v kapitole 3.

Dizertační práce je zaměřena na přístrojový test TUG s využitím nositelných senzorů a tlakocitlivého chodníku, přičemž uvedené bylo použito pro měření pohybu na půdě Neurologické kliniky 1. lékařské fakulty Univerzity Karlovy a Všeobecné fakultní nemocnice v Praze.

Kapitola 2

Současný stav řešené problematiky

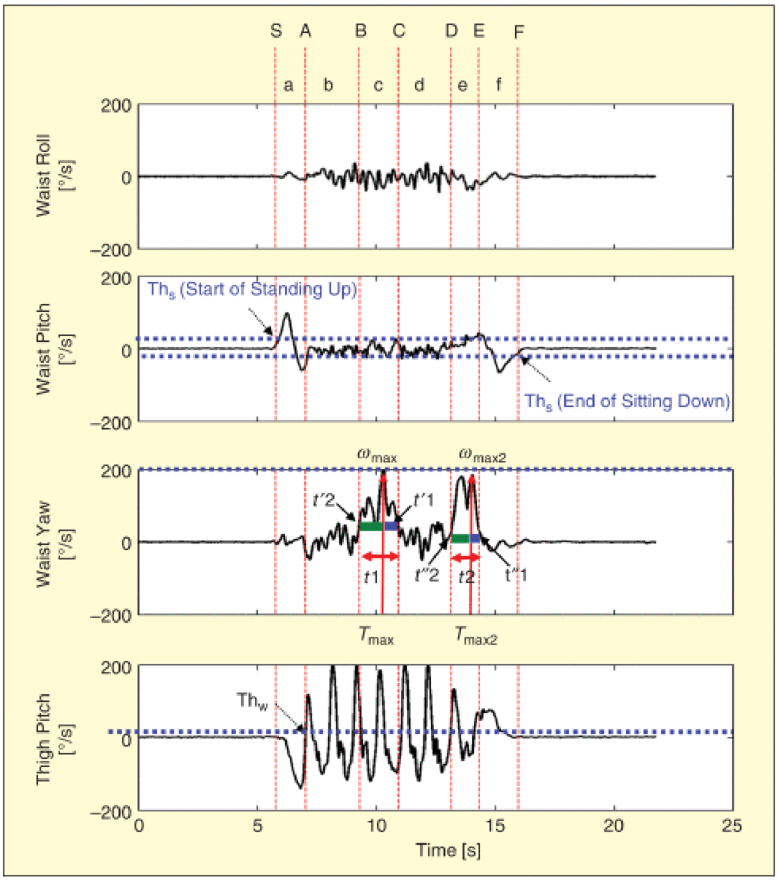
Kapitola je rozdělena do 3 částí. První část (podkapitola "Využití přístrojového testu TUG") obsahuje rešerši využití přístrojového testu TUG a zpracování naměřených signálů (např. detekované komponenty, pohybové parametry popisující vykonávání testu TUG). Druhá podkapitola je věnována analýze přístrojového testu TUG z pohledu spolehlivosti vypočítaných pohybových parametrů. Poslední podkapitola shrnuje dosažené výsledky zpracování a analýzy pohybových parametrů a nastiňuje příležitosti pro další výzkum.

2.1 Využití přístrojového testu TUG

Mezi počáteční studie využívající přístrojový TUG patří práce Narayanan a kol. [10, 11, 12], kteří jej využili pro určení rizika pádu seniorů. Na základě dat, konkrétně mediolaterální složky zrychlení, z jednoho 3-osého akcelerometru umístěného u pasu subjektu automaticky segmentovali TUG a hodnotili dobu trvání jednotlivých komponent (sed-do-stoje, chůze 1, otáčení, chůze 2, otáčení-do-sedu).

Také Higashi a kol. [13] patří k pionýrům přístrojového měření TUG. Jedna inerciální jednotka zaznamenávající zrychlení a úhlovou rychlost (obrázek 1) byla umístěna na dorzální straně v oblasti pasu a druhá na laterální straně stehna (obrázek 2.2). Komponenty sed-do-stoje, otáčení 1 (otáčení na konci 3 m chůze), otáčení 2 (otáčení před usednutím na křeslo), usednutí byly identifikovány na základě úhlové rychlosti senzoru umístěného v pase, pro chůzi byl využit stehenní senzor. Následně srovnávali mezi skupinami subjektů dobu trvání jednotlivých komponent, kadenci a RMS (root mean square) vypočítané ze zrychlení.

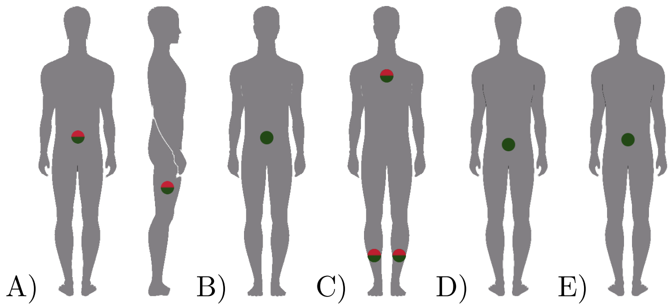
Gillain a kol. [14] připevnil 3-osý akcelerometr v dolní oblasti zad (ko-



Obrázek 2.1: Typické úhlové rychlosti naměřené ve studii autorů Higashi a kol. [13] (převzato z [13]).

merčně dostupný systém pro analýzu chůze Locometrix®) a pro srovnání skupin participantů použil parametry popisující komponentu chůze: rychlost chůze, délku kroku, frekvenci kroků, symetrii amplitudy zrychlení, variabilita amplitudy zrychlení mezi chůzovými cykly. Způsob identifikace komponent testu TUG systémem Locometrix jsou v článku pouze referencovány (nikoli popsány), ale odkazovaný web již není dostupný [ke dni 20.2.2019].

Ačkoliv Marschollek a kol. [15] ve své práci také akcelerometrem (obrázek 2.2) měřil subjekty při vykonávání celého testu TUG, pro klasifikaci padačů a nepadačů použili pouze chůzová data a analyzovali jejich spektrální hustotu. Pouze chůzi použili také v další studii [16], ve které na základě chůzových dat vypočítali energetický výdej, délku a trvání kroku, periodicitu (via směrodatnou odchylku), počet kroků a kývání pánve při chůzi. Tyto parametry

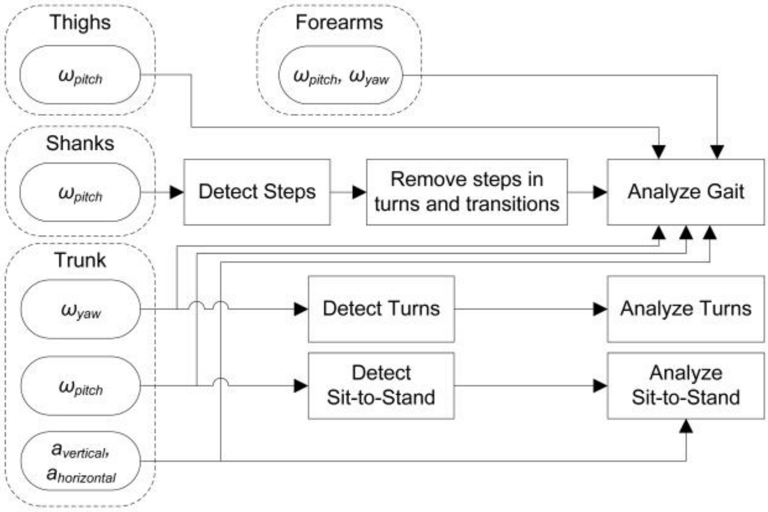


Obrázek 2.2: Umístění senzorů. A) gyro-akcelerometry umístěné v oblasti pasu a na stehně [13]; B) akcelerometr na sponě pásku [15]; C) gyro-akcelerometry na hrudi a bércích [17]; D) akcelerometr v oblasti zad na 5. lumbálním obratli [18]; E) akcelerometr v oblasti zad na 3. lumbálním obratli [19].
Vysvětlivky: zelená - akcelerometr, červeno-zelená - gyro-akcelerometr.

uplatnili při klasifikaci padačů a nepadačů.

Zcela odlišné umístění akcelerometru zvolil King a kol. [20]. Participanti nosili 3-osý akcelerometr připevněný na uchu. Během vyhodnocování byla každá komponenta TUG ručně označena pro následné zpracování. Ze získaného signálu akcelerace následně vyhodnocovali počet vrcholů (odpovídá počtu kroků) a čas vykonání TUG.

O větší rozmach využívání přístrojového testu TUG se zasloužil převážně Salarian a kol. [21, 22, 23, 24]. Umístili na tělo subjektu 7 gyro-akcelerometrů (1x 3D akcelerometr a 2D gyroskop na sternu, 2x 2D gyroskop symetricky na předloktích, 2x 1D gyroskop symetricky na stehnech, 2x 1D gyroskop symetricky na lýtkách) a automaticky segmentovali TUG na 5 částí (sed-do-stoje, chůze 1, otáčení, chůze 2, otáčení-do-sedu). K detekci komponent TUG využili signál úhlového zrychlení hrudního senzoru. Schéma algoritmu detekce je zobrazeno na obrázku 2.3. Zároveň také provedli výpočet a hodnocení spolehlivosti 35 parametrů u pacientů s PD a referenční skupinou. Tyto parametry popisují všech 5 komponent TUG a zahrnují časoprostorové parametry (kadence, doby trvání fází chůzového cyklu, délka kroku, počet kroků), popisné parametry úhlové rychlosti (průměrná úhlová rychlost, maximální úhlová rychlost) a parametry odvozených z úhlové rychlosti (rozsahy pohybů trupu, dolních i horních končetin). Příkladem využití tohoto přístupu k analýze testu TUG z poslední doby jsou práce [25, 26, 27, 28, 29, 30]. K jeho rozšíření pomohl i fakt, že na jeho základě vznikl komerčně dostupný systém pro analýzu testu TUG - APDM Mobility Lab System (Opal sensors, APDM, Portland, OR, USA). Další studie používající pro analýzu pohybu při testu TUG tento přístup či přímo systém APDM, nejsou v rešerši dále po-



Obrázek 2.3: Algoritmus detekce komponent testu TUG podle Salarian a kol. [21] (převzato z [21]).

pisovány, neboť aplikují existující přístup ke zpracování dat, ale nepřinášejí nové metody či parametry. Nutno poznamenat, že práce Salariana a kol. není využívána jen při analýze celého testu TUG. Jejich práce je hojně využívána i při samostatném zpracování a analýze otáčení, které je součástí testu (viz příloha A).

Greene a kol. [17, 31, 32] použili 44 parametrů odvozených z úhlové rychlosti měřené pomocí dvou 3-osých gyro-akcelerometrů upevněných symetricky na holeních (obrázek 2.2). Sada parametrů obsahovala časoprostorové parametry chůze (počet kroků, počet chůzových cyklů, doba chůze, kadence, doba trvání různých fází chůzového cyklu a jejich variabilita), popisné parametry úhlové rychlosti (minimální, maximální a průměrná rychlost ve všech 3 osách) a rychlost otáčení. V navazující práci [33] byly přidány popisné parametry akcelerace u komponent sed-do-stoje a stoj-do-sedu. Také z tohoto řešení kvantifikace testu TUG se stal komerčně dostupný produkt - Kinesis QTUG (Kinesis Health Technologies Ltd., Dublin, Ireland) a je využíván v mnoha studiích [34, 35].

Weiss a kol. [36] se zaměřili na kvantitativní analýzu komponent sed-do-stoje and stoj-do-sedu. Detekci komponent založili na zrychlení (anterio-posterior složky) naměřeného 3-osým akcelerometrem umístěným v dolní oblasti zad. U obou komponent hodnotili dobu trvání, míru třesu, rozsah, medián a směrodatnou odchylku zrychlení.. Kolektiv autorů později rozšířil hodnocení na všechny komponenty testu, tj. sed-do-stoje, chůze, otáčení, stoj-do-sedu [37]. Pro srovnání otáčení a chůze dvou skupin subjektů využili počet kroků a popisné parametry akcelerace a úhlové rychlosti (rozsah hodnot). Pro chůzi ještě vypočítali pravidelnost kroků [38].

Srovnání obvyklého testu TUG a testu TUG prováděného ve vodě pomocí sEMG (surface EMG) provedl Cuesta-Vargas a kol. [39]. Sedm senzorů bylo rozmístěno na pravé půlce těla subjektu a hodnoceným parametrem byla maximální isometrická kontrakce.

Mariani a kol. [40] provedli analýzu testu TUG u pacientů s Parkinsonovou chorobou a referenční skupiny pomocí 3-osého akcelerometru umístěného na nártu. Ve své práci identifikovali tři komponenty: započetí chůze, ukončení chůze, plynulá chůze. Kromě rozdílnosti časoprostorových parametrů mezi skupinami analyzovali i jejich spolehlivost.

Data z akcelerometru integrovaného do trička v oblasti hrudníku byl použit k detekci sed-do-stoje a stoj-do-sedu komponent a následně vyhodnotili dobu jejich trvání mezi skupinami subjektů [41].

Palmerini a kol. detekovali komponenty sed-do-stoje, chůze, chůze-do-sedu ze signálu zrychlení a otáčení označili manuálně [18]. Umístění senzoru je znázorněno na obrázku 2.2. U každé komponenty hodnotili dobu trvání, RMS a třes. U chůze navíc hodnotili časoprostorové parametry kroku (doba trvání fází, směrodatná odchylka, koeficient variace), koordinaci fází mezi kroky a harmonický poměr.

Strohrmann a kol. [42] ve své studii pohybu dětí po mozkové obrně využili 10 senzorů (3-osé gyro-akcelerometry). Kroky byly detekovány pomocí akcelerace senzorů na obou nártech a byly hodnoceny délky trvání kroků je jejich fází.

Narozdíl od předchozích prací Tmaura a kol. [43] rozdělili komponenty sed-do-stoje a stoj-do-sedu na 2 pod-fáze. Tím získali 8 komponent testu sit-bend, bend-stand, chůze 1, otáčení 1, chůze 2, otáčení 2, stand-bend and bend-sit a hodnotili čas potřebný k dokončení jednotlivých fází. Automatická detekce komponent využívala úhlovou rychlost senzorů (akcelerometry a gyroskopy) umístěných v dolní části zad a obou stehnech subjektů. Dále také hodnotili kadenci, RMS zrychlení i úhlové rychlosti a rychlost chůze [44].

SankarPandi a kol. [45] zpracovali 40 parametrů, které počítali pro celý TUG bez rozdělení na komponenty. Všech 40 parametrů byly popisné parametry akcelerace naměřené 3-osým akcelerometrem na zápěstí (průměrná intenzita signálů, směrodatná odchylka, kovariance mezi signály z různých os, plocha pod signály).

Vervoort a kol. [19] navrhli vlastní detektor komponent založený na vlnkové transformaci a pro komponenty TUG vypočítali 72 parametrů. Tyto parametry čerpali z předchozích publikací. Umístění senzoru je znázorněno na obrázku 2.2.

Ponti a kol. [46] TUG nerozdělovali na komponenty a ze signálu zrychlení (akcelerometr umístěný v oblasti pasu) vypočítali pro celý TUG 10 parametrů (power spectral entropy, power spectrum peak frequency, power spectrum peak, weighted power spectrum peak).

Witchel a kol. [47] umístili gyro-akcelerometr na každé stehno a třetí do dolní části zad. Pro následnou analýzu sed-do-stoje využili pouze úhlovou rychlost (maximum, plocha pod křivkou, hladkost).

Caroni a kol. [48] rozdělili TUG manuálně na komponenty sed-do-stoje, chůze 1, otáčení 1, chůze 2, otáčení 2, otáčení-do-sedu. Pro další analýzu ze signálu gyro-akcelerometru umístěného v dolní části zad vypočítali doby trvání komponent, průměrné úhlové rychlosti a RMS zrychlení.

V posledních letech se na trhu objevil další inerciální systém pro analýzu pohybu - G-Walk (BTS Bioengineering S.p.A., Italy). Systém obsahuje 1 senzor umístěný v dolní oblasti zad, automaticky detekuje komponenty testu TUG, počítá dobu trvání jednotlivých komponent, časoprostorové parametry chůze a úhly flexe/extenze při sed-do-stoje a otáčení.

Souhrnný přehled analyzovaných komponent a použitých parametrů je uveden v tabulkách 2.1-2.4

Autoři	Sed-do-stoje	Chůze	Otáčení	Otáčení-do-sedu	HW	Algoritmus detekce komponent
[10, 11, 12]	ano	ano	ano	ano	1x 3D akcelerometr	NP
[13]	ano	ano	ano	ano	2x 3D gyro-akcelerometr	na základě úhlové rychlosti
[14]	-	ano	-	-	1x 3D akcelerometr	NP
[15]	-	ano	-	-	1x 3D akcelerometr	NP
[16]	-	ano	-	-	1x 3D akcelerometr	referencována diplomová práce v němčině
[17, 31]	-	ano	ano	-	2x 3D gyro-akcelerometr	NP
[33]	ano	ano	ano	ano	2x 3D gyro-akcelerometr	na základě akcelerace
[20]	-	ano	-	-	1x 3D akcelerometr	manuálně
[21]	ano	ano	ano	ano	7 gyro-akcelerometrů (kombinace 3D akcelerometru, 1D a 2D gyroskopů)	na základě úhlové rychlosti
[36]	ano	-	-	ano	1x 3D akcelerometr	na základě akcelerace
[37]	ano	ano	ano	ano	1x 3D gyro-akcelerometr	na základě úhlové rychlosti
[39]	-	-	-	-	1x sEMG senzor	BR
[40]	-	ano	-	-	1x 3D akcelerometr	na základě akcelerace
[41]	ano	-	-	ano	1x 3D akcelerometr	na základě akcelerace
[42]	-	ano	-	-	10x 3D akcelerometr	NP
[18]	ano	ano	ano	ano	1x 3D akcelerometr	manuálně
[43]	ano	ano	ano	ano	1x 3D akcelerometr 3x 1D gyroskop	na základě úhlové rychlosti
[45]	-	-	-	-	1x 3D akcelerometr	BR
[19]	ano	ano	ano	ano	1x 3D gyro-akcelerometr	[37]
[46]	-	-	-	-	1x 3D akcelerometr	BR
[47]	ano	-	-	-	3x 3D gyro-akcelerometr	[37]
[48]	ano	ano	ano	ano	1x 3D gyro-akcelerometr	manuálně

Tabulka 2.1: Přehled analyzovaných komponent, algoritmů jejich detekce a využitého HW.
Vysvětlivky: NP - nepublikováno, BR - bez rozdělení na komponenty

Autoři	Celková doba trvání	Časoprostorové parametry	Popisné parametry akcelerace	Popisné parametryi úhlové rychlosti	Ostatní
[10, 11, 12]	ano	-	-	-	-
[13]	ano	ano	ano	-	
[14]	ano	ano	ano	-	-
[15]	-	-	ano	-	-
[16]	-	ano	ano	-	ano
[17, 31]	ano	ano	-	ano	-
[33]	ano	ano	ano	ano	-
[20]	ano	ano	-	-	-
[21]	ano	ano	ano	ano	-
[40]	-	ano	-	-	-
[42]	-	ano	-	-	-
[43]	ano	-	-	-	-
[37]	ano	ano	ano	ano	
[19]	ano	ano	ano	ano	ano
[18]	ano	ano	ano	ano	ano
[48]	ano	-	-	-	ano

Tabulka 2.2: Přehled typů parametrů využitých při analýze chůzové komponenty.

Autoři	Celková doba trvání	Časoprostorové parametry	Popisné parametry akcelerace	Popisné parametryi úhlové rychlosti	Ostatní
[10, 11, 12]	ano	-	-	-	-
[13]	ano	-	-	-	-
[21]	ano	-	-	ano	-
[33]	ano	-	ano	ano	-
[36]	ano	-	ano	-	ano
[41]	ano	-	-	-	-
[43]	ano	-	-	-	-
[37]	ano	-	ano	ano	ano
[48]	ano	-	-	-	-
[47]	ano	-	-	ano	ano
[19]	ano	-	ano	ano	ano
[18]	ano	-	ano	ano	ano

Tabulka 2.3: Přehled typů parametrů využitých při analýze komponenty sed-do-stoje.

Autoři	Celková doba trvání	Časoprostorové parametry	Popisné parametry akcelerace	Popisné parametryi úhlové rychlosti	Ostatní
[10, 11, 12]	ano	-	-	-	-
[13]	ano	ano	ano	-	-
[17, 31]	ano	-	-	ano	-
[21]	ano	ano	-	ano	-
[43]	ano	-	-	-	-
[37]	ano	ano	ano	ano	-
[48]	ano	-	-	ano	-
[18]	ano	ano	ano	ano	-
[19]	ano	ano	ano	ano	ano

Tabulka 2.4: Přehled typů parametrů využitých při analýze komponenty otáčení.

2.2 Analýza přístrojového testu TUG

Smith a kol. [49] testovali spolehlivost parametrů chůze a otáčení u starších osob. Protože se test TUG používá k vyhodnocení funkčního stavu různých skupin subjektů, je nutné tyto parametry vyhodnotit pro každou skupinu subjektů. Salarian a kol. [21] sice zkoumali spolehlivost přístrojového testu TUG smíšené skupiny sestávající ze starších osob a pacientů s Parkinsonovou chorobou, nehodnotili ale spolehlivost pro každou z těchto skupin zvlášť. Craig a kol. [28] porovnali spolehlivost testu u starších osob a pacientů s roztroušenou sklerózou. Zaměřili se pouze na komponentu chůze. Tyto studie, které hodnotily spolehlivost parametrů přístrojového testu TUG, zkoumaly údaje shromážděné během několika sezení (inter-session) ze stejného dne [21] nebo během několika dnů [49, 28]. Newman a kol. [29] analyzovali spolehlivost testu v rámci jednoho sezení (intra-session) u zdravých dětí a u dětí s diagnózou traumatického poranění mozku.

2.3 Závěry z provedené rešerše

Z výše provedené rešerše vyplývá, že majoritní podíl studií využívající přístrojový test TUG k analýze pohybu vychází z přístupu autorů Salarian a kol. [21] a Greene a kol. [17]. Společným rysem obou přístupů je segmentace signálů na komponenty a následný výpočet parametrů popisující tyto komponenty. U sed-do-stoje, otáčení a otáčení-do-sedu komponent jde především o popisné charakteristiky úhlové rychlosti (např. průměrná či maximální rychlost). U chůzové komponenty to jsou obvyklé časo-prostorové parametry (např. délka kroku, doby trvání fází chůzového cyklu).

2.3.1 Komponenta sed-do-stoje

Zaměříme-li se na jednotlivé komponenty samostatně, lze u komponenty sed-do-stoje říci, že zrychlení [37, 44, 50] i úhlová rychlost [21, 44] slouží jako zdrojové signály pro výpočet parametrů. Tyto parametry zahrnují minimální hodnotu [50], maximální hodnotu [50, 44, 21], průměrnou hodnotu [37, 21], medián [50] a směrodatnou odchylku [37] signálů. V rozsáhlé rešerši prací zabývajících se analýzou přechodů sed-do-stoje Millor a kol. [51] shrnul dosavadní výsledky a poznamenal, že na rozdíl o zrychlení úhlová rychlost přechodu sed-do-stoje testu TUG zatím neposkytla žádné smysluplné informace. Ačkoli byla spolehlivost některých parametrů sed-do-stoje již analyzována [21, 29], **dosud neexistuje žádná studie, která by se zabývala**

analýzou spolehlivosti zdrojových signálů komponenty sed-do-stoje, tj. úhlové rychlosti a zrychlení. Navíc pro relevantní výsledky analýzy pohybu a následnou adekvátní interpretaci je potřeba použít vhodné parametry. Základem pro výběr parametru je znalost vzoru analyzovaného signálu. **Žádná z předchozích studií se nevěnovala výskytu společného vzoru v signálech zrychlení či úhlové rychlosti komponenty sed-do-stoje**.

Dále, v nedávných studiích byly použity dva přístupy k hodnocení komponenty sed-do-stoje. První přístup analyzoval celou komponentu najednou [21, 37, 50]. Druhý přístup, rozděluje komponentu na dvě fáze: sed-předklon a předklon-stoj a poté hodnotí každou fázi samostatně. Ačkoli řada studií pracuje s přístrojovým testem TUG, jen několik z nich zahrnovalo hodnocení sed-do-stoje [21, 37, 52, 50]. **Žádná z předchozích studií nesrovnala oba přístupy hodnocení sed-do-stoje, tj. hodnocení komponenty sed-do-stoje jako celku a hodnocení jednotlivých fází samostatně**.

2.3.2 Komponenta chůze

Chůzová komponenta je nejčastěji hodnocenou komponentou testu TUG. Obecně lze říci, že charakteristiky chůze jsou hojně rozšířeným měřítkem při hodnocení patologií, stability, zvýšeného rizika pádu, účinku věku na mobilitu, poklesu kognitivních funkcí, apod. Při hodnocení chůzové komponenty přístrojového testu TUG jsou adoptovány parametry ze široké škály parametrů používaných v "tradiční" analýze chůze. Jde převážně o časoprostorové parametry. Inerciálních senzory ale dávají příležitost k hodnocení chůzového cyklu jako celku. Zatímco časo-prostorové parametry poskytují diskrétní informace, např. délka kroku, nepopisují celé křivky, tj. vývoj v čase. Například dva chůzové cykly mohou mít podobné délky, ale různé křivky. Přestože časo-prostorové parametry se ukázaly jako velmi užitečné, metody založené na hodnocení křivek (průběh signálu v čase) mohou být více informativní [53]. **Dosud žádná ze studií nehodnotila časový průběh signálu chůzové komponenty**.

Chůzová komponenta se skládá ze dvou částí: chůze před otočkou a chůze po otočce. Hodnocení komponent testu TUG není standardizováno a některé studie hodnotí každou z částí zvlášť [54], jiné studie hodnotí obě části jako celek [37], zatímco většina studií neuvádí zda je výpočet parametrů chůze založen na obou částech nebo jen některé z nich [55, 28, 31, 32, 49]. Nesoulad týkající se možných rozdílů v chůzových parametrech před otočením a po otáčení může vést k nesrovnalostem při porovnání výsledků mezi studiemi. **Žádná studie se dosud nezbývala srovnáním parametrů chůze před otočením a po otočení**.

2.3.3 Komponenta otáčení

U komponenty otáčení je stav analýzy a použitých parametrů obdobný jako u komponenty sed-do-stoje. Komponenta otáčení je nejčastěji hodnocena počtem kroků nebo charakteristikami signálu zrychlení či úhlové rychlosti (např. průměr). Současně s rostoucím zájmem o analýzu komponenty otáčení (viz příloha A)) by měly být vyvíjeny adekvátní parametry pro jejich hodnocení. I v případě komponenty otáčení mohou být metody, které berou v úvahu celý průběh signálu, přínosné. **Žádná z předchozích studií se při analýze komponenty otáčení nevěnovala využití metody, která hodnotí průběh signálu v čase**.

Obdobně jako u komponenty sed-do-stoje ani u komponenty otáčení zatím nebyla provedena analýza signálů, které jsou základem pro výpočet dalších parametrů. **Tj. u úhlové rychlosti a zrychlení komponenty otáčení dosud nebyla provedena analýza spolehlivosti signálu ani analýza výskytu vzoru společného pro všechny subjekty**.

2.3.4 Komponenta otáčení-do-sedu

Poslední vykonávaná část testu TUG je v některých studiích rozdělena na 2 části (otáčení a stoj-do-sedu), v jiných jde o 1 komponentu (otáčení-do-sedu). Ani u jednoho z těchto dvou případů ale nedošlo k častějšímu využití při hodnocení (např. srovnání různých skupin subjektů).

Obdobně jako u komponent sed-do-stoje a otáčení, **dosud nebyla u komponenty otáčení-do-sedu provedena analýza opakovatelnosti a společného vzor zdrojových signálů**, tj. úhlové rychlosti a zrychlení.

Kapitola 3

Cíle

Cílem disertační práce je *rozbor signálů komponent přístrojového testu Timed Up & Go vzhledem k analýze pohybu a navrhnout kvantitativní metody jejich hodnocení.*

Na základě provedené rešerše a znalostí byly pro dosažení výše uvedeného cíle stanoveny tyto dílčí úkoly:

1. Pro komponentu sed-do-stoje:
   - Cíl 1: Rozbor signálů komponenty sed-do-stoje vzhledem ke kvantitativní analýze pohybu.
   - Cíl 2: Analýza rozdělení komponenty sed-do-stoje na fáze.
2. Pro chůzovou komponentu:
   - Cíl 3: Analýza opakovatelnosti chůzových parametrů při opakovaném měření.
   - Cíl 4: Analýza samostatného hodnocení chůzových komponent před a po otáčení.
3. Pro komponentu otáčení:
   - Cíl 5: Rozbor signálů komponenty otáčení vzhledem ke kvantitativní analýze pohybu.
   - Cíl 6: Návrh přístupu k hodnocení komponenty otáčení zohledňující tvar signálu.
4. Pro komponentu otáčení-do-sedu
   - Cíl 7: Rozbor signálů komponenty otáčení-před-sedem vzhledem ke kvantitativní analýze pohybu.

Kapitola 4

Metody

Tato kapitola popisuje participanty, protokol měření a získávání dat. Způsob zpracování naměřených dat je pak popsán v samostatných kapitolách, z nichž každá odpovídá jednomu cíli dizertační práce. Tyto kapitoly vycházejí z prací publikovaných v impaktovaných časopisech (kapitola 6.1, kapitola 6.2, kapitola 7.1, kapitola 7.2, kapitola 8.1) a konferenčních příspěvků (kapitola 5.2).

Data použitá v dizertační práci pocházejí ze dvou nezávislých studií. V obou případech se jedná o studie prováděné na Neurologické klinice 1. LF UK a VFN v Praze.

4.1 Participanti

4.1.1 Studie 1

Studie se zúčastnili participanti s Parkinsonovou chorobou a referenční skupina. Referenční skupina byla složená ze starších osob bez diagnostikované neurodegenerativní choroby. Pacient byl považován jako způsobilý, pokud byl schopen pohybovat se samostatně bez pomůcek pro chůzi ve stavu s medikací (ON) i bez medikace (OFF). Podmínkou byla délka onemocnění minimálně 6 let a zřetelná, příznivá odezva na dávku medikamentů (levodopa) trvající nejméně dvě hodiny. Detailní popis klinického hodnocení subjektů lze nalézt v publikaci Hoskovcová a kol. [56].

4.1.2 Studie 2

Studie se účastnily 3 skupiny osob: denovo pacienti s Parkinsonovou chorobou, osoby s REM sleep behavior disorder a referenční skupina starších osob bez diagnostikované neurodegenerativní choroby.

V rámci dizertační práce byla zpracována pouze data subjektů s Parkinsonovou chorobou a referenční skupiny. Naměřená kinematická data byla zpracovávaná a výsledky publikovány postupně v průběhu studie, a proto se počty subjektů v jednotlivých publikacích liší.

4.2 Protokol měření

4.2.1 Studie 1

Všichni pacienti podstoupili měření jak ve stavu bez medikace (OFF) tak i ve stavu s medikací (ON). Hodnocení v obou stavech proběhlo ve stejný den. Všichni participanti absolvovali prodloužený Timed Up & Go test [22]. Každý participant byl sledován a měřen zatímco vstal z křesla, šel 7 metrů, otočil se, šel zpět a znovu se posadil. Každý participant provedl TUG test dvakrát ve stavu ON i ve stavu OFF. Nejdříve byli hodnoceni ve stavu OFF, a poté ve stavu ON po podání 150% jejich běžné ranní dávky medikamentů (levodopa). Participanti z referenční skupiny prováděli TUG pouze jednou.

4.2.2 Studie 2

Všichni participanti prováděli prodloužený test Timed Up & Go [57]: vstali z křesla, šli 10 metrů obvyklou rychlostí chůze, otočili se, vrátili se zpět a posadili se znovu na křeslo. Tento test byl proveden dvakrát za každé ze tří podmínek: (1) TUG, (2) TUG s manuální úlohou (participant nesl sklenici vody) a (3) TUG s kognitivní úlohou (postupné odečítání čísla 3 od 100). Testy byly prováděny vždy ve výše popsaném pořadí.

4.3 Získávaní dat

Kinematická data obou studií byla zaznamenávána pomocí přenosných senzorů se zabudovaným akcelerometrem a gyroskopem (Xsens MTx; Enschede, Netherlands) vzorkovací frekvencí 100 Hz. Při měření bylo použito 5 inerciálních senzorů, které byly rozmístěny na těle měřeného subjektu takto: symetricky na obou dolních končetinách na laterální straně holeně (4 cm nad kotníkem), symetricky na obou horních končetinách na dorzální straně zápěstí, a na hrudi (2 cm pod sternálním výběžkem), viz obrázek 4.1. Pro potřeby této práce byla využita data ze senzorů umístěných na dolních končetinách a hrudi.

Obrázek 4.1: A) Umístění inerciálních senzorů na těle participanta. B) Dispozice měření v prostorách Neurologické kliniky 1. lékařské fakulty Univerzity Karlovy a Všeobecné Fakultní Nemocnice v Praze.

4.3.1 Studie 2

Kromě inerciálních měřících jednotek byl použit i tlakocitlivý chodník GAITRite (Platinum model GAITRite®, CIR System Inc., Franklin, USA). Chodník (5.15 m dlouhý, 0.9 m široký) byl umístěn 2.43 m od židle, uprostřed dráhy, po které participanti chodili (obrázek 4.1).

Kapitola 5

Komponenta sed-do-stoje

5.1 Cíl 1: Rozbor signálů komponenty sed-do-stoje vzhledem ke kvantitativní analýze pohybu

Přestože existuje několik parametrů hodnotících přechod sed-do-stoje založených na signálech získaných pomocí inerciálních senzorů, nebyla publikována žádná práce analyzující tyto signály a jejich vhodnost pro výpočet parametrů. Pro posouzení vhodnosti byla provedena analýza sdíleného vzoru a variability signálů v rámci skupiny subjektů.

5.1.1 Zpracování

Komponenta sed-do-stoje byla detekována za základě úhlové rychlosti předklonu. Začátek komponenty je detekován jako úhlová rychlost přesahující prahovou hodnotu 10 °/s [13]. Konec komponenty byl identifikován jako hodnota nižší než 10 °/s.

Analýza vzoru signálu

Pro analýzu sdíleného vzoru signálů byla použita metoda vnitrotřídní korelace (intra-class correlation, ICC), dvoucestné náhodné efekty, konzistence, jedno měření. ICC byla vypočtena pro každý bod podél celé křivky.

Stanovení predikčního pásma

Variabilita signálů mezi subjekty byla zkoumána pomocí predikčních pásem [58, 59] metodou bootstrap. 95% predikční pásma byla vypočtena s 1000 bootstrap vzorky (podrobnosti v Lenhoff a kol. [58]). Pravděpodobnost pokrytí byla stanovena křížovou validací.

5.1.2 Výsledky

Analýza vzoru signálu

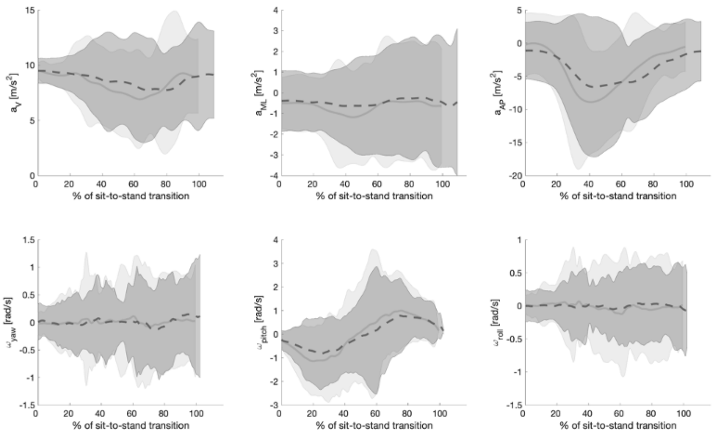
Úhlová rychlost předklonu ukázala nejlepší shodu vzoru signálu mezi subjekty v obou skupinách ($0.50 < \rho < 0.75$). Antero-posteriorní zrychlení u kontrolní skupiny také vykazovalo mírnou shodu vzoru signálu mezi subjekty ($0.50 < \rho < 0.75$). Jiné signály prokázaly slabou shodu vzoru signálu ($\rho < 0.50$), tabulka 5.1.

Stanovení predikčního pásma

Predikční pásma v obou skupinách jsou uvedena na obrázku 5.1. Výsledky křížové validace viz tabulka 5.1. Pro NOR se odhadované skutečné dosažené pokrytí pohybovalo od 86% do 93% pro křivky zrychlení a od 72% do 86% pro úhlové rychlosti. U PD byly výsledky zrychlení a úhlové rychlosti mírně nižší než u NOR (pohybovaly se od 80% do 87%, resp. 74% až 77%).

	ρ (95% interval spolehlivosti)		pravděpodobnost pokrytí	
	NOR	PD	NOR	PD
a_V	0.34* (0.3,0.4)	0.22* (0.19,0.27)	0.86	0.80
a_{ML}	0.07* (0.06,0.1)	0.01* (0,0.02)	0.93	0.87
a_{AP}	0.69* (0.65,0.74)	0.45* (0.41,0.52)	0.86	0.87
ω_{yaw}	-0.01 (-0.01,0)	0.06* (0.05,0.09)	0.72	0.77
ω_{pitch}	0.67* (0.63,0.72)	0.62* (0.57,0.67)	0.86	0.74
ω_{roll}	0.01* (0,0.03)	-0.01 (-0.01,0)	0.79	0.77

Tabulka 5.1: Hodnocení společného vzoru signálů akcelerace a úhlových rychlostí (koeficient vnitrotřídní korelace (ρ) a 95% interval spolehlivosti, pravděpodobnost pokrytí).
Vysvětlivky: * - statisticky významný rozdíl ($p<0.05$); NOR - kontrolní skupina; PD - pacienti s Parkinsonovou chorobou



Obrázek 5.1: Kinematická data těla během přechodu sed-to-stoje u kontrolní skupiny a ve skupině pacientů s Parkinsonovou chorobou.
Světle šedá oblast - predikční pásmo kontrolní skupiny, tmavě šedá oblast - predikční pásmo skupiny s Parkinsonovou chorobou, plná světle šedá čára - střední hodnota signálu kontrolní skupiny, přerušovaná tmavě šedá čára - střední hodnota signálu skupiny s Parkinsonovou chorobou

5.1.3 Závěr

Výše uvedené výsledky ukazují, že úhlová rychlost předklonu má nejsilnější společný vzor ze všech analyzovaných signálů v obou vyšetřovaných skupinách, tj. PD a NOR. Úhlová rychlost vybočení neměla statisticky významný výsledek v NOR. Na základě těchto zjištění je možné považovat křivku úhlové rychlosti předklonu jako nejvhodnější pro analýzu komponenty sed-do-stoje, a dále doporučit další analýzu křivky úhlové rychlosti vybočení.

5.1.4 Vlastní publikace

Slavka Netukova, Ondrej Klempir, Radim Krupicka, Petr Dusek, Patrik Kutilek, Zoltan Szabo, Evžen Růžička. The Timed Up & Go test sit-to-stand transition: which signals measured by inertial sensors are viable route for continuous analysis?.
(v recenzním řízení)

Plný text rukopisu viz příloha B.

5.2 Cíl 2: Analýza rozdělení komponenty sed-do-stoje na fáze

Nedávné studie využily dva přístupy k hodnocení komponenty sed-do-stoje. První přístup analyzoval celou komponentu najednou [21, 36, 60]. Druhý přístup upravuje hodnocení komponenty tak, že ji rozdělí na dvě fáze: sed-předklon a předklon-stoj [52]. Navíc, Millor a kol. [51] v rozsáhlé rešerši uvedli, že úhlová rychlost komponenty sed-do-stoje v testu TUG zatím neposkytla žádné smysluplné informace.

5.2.1 Zpracování

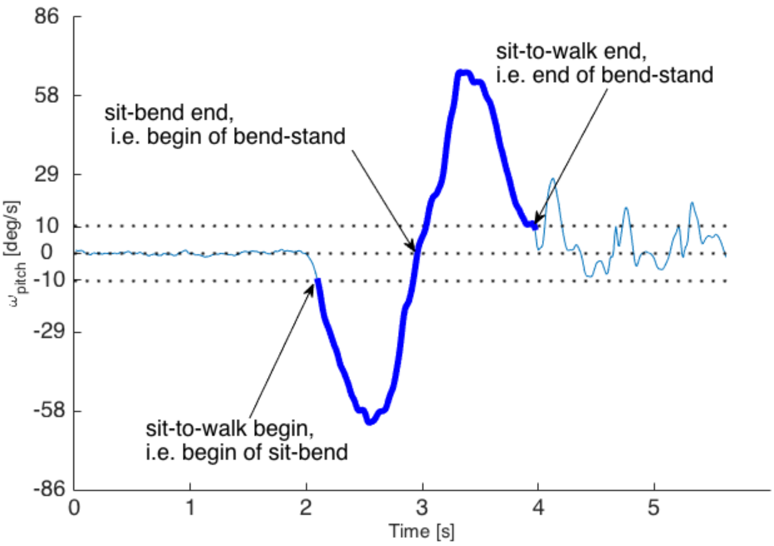
Pro zpracování komponenty sed-do-stoje byla použita úhlová rychlost naměřená hrudním inerciálním senzorem. Přechod sed-do-stoje byl detekován prahovým detektorem jako pohyb s úhlovou rychlostí předklonu vyšší než 10 °/s [13]. Znaménko úhlové rychlosti indikuje směr otáčení: po směru nebo proti směru hodinových ručiček. Proto byl začátek sed-do-stoje, tj. začátek fáze sed-předklon, detekován jako úhlová rychlost menší než -10 °/s. Průchod signálu úhlové rychlosti nulou znamená změnu směru rotace. V případě sed-do-stoje jde o konec fáze předklánění, tj. začátek fáze předklon-stoj (obrázek 5.2). Konec sed-do-stoje, tj. konec fáze předklon-stoj, byl identifikován jako hodnota nižší než 10 °/s.

Pro hodnocení sed-do-stoje byl použit průměr, maximální hodnota a rozptyl úhlové rychlosti předklonu a doba trvání. Všechny 4 parametry byly vypočteny pro obě dílčí fáze (sed-předklon, předklon-stoj) a celý přechod. Celkem tedy 12 hodnot parametrů pro každého participanta.

Pro porovnání skupiny PD s kontrolní skupinou byl použit neparametrický Wilcoxonův rank sum test. Hladina významnosti byla nastavena na $p<0.05$. Hodnocení spolehlivosti parametrů bylo provedeno prostřednictvím koeficientu vnitrotřídní korelace (ρ), absolutní shoda.

5.2.2 Výsledky

V tabulce 5.2 lze vidět, že ze všech 4 testovaných parametrů, se ukázala nízká spolehlivost ($\rho < 0.50$) ve všech třech případech (celá komponenta sed-do-stoje, sed-předklon, předklon-stoj) u 3 parametrů v kontrolní skupině a u 1 parametru ve skupině pacientů s PD. Pro kontrolní skupinu to byly parametry: doba trvání fáze, průměr a rozptyl úhlové rychlosti. U pacientů s PD to byl pouze parametr doba trvání. Parametr maximální hodnota úhlové



Obrázek 5.2: Graf znázorňující úhlovou rychlost jednoho subjektu.
Vysvětlivky: tučně modře - komponenta sed-do-stoje.

rychlosti v kontrolní skupině vykazovala vyšší spolehlivost (střední, $\rho > 0.50$) ve fázi předklon-stoj než v ostatních případech (špatná, $\rho < 0.50$). Parametry průměr a rozptyl v PD měly nízkou spolehlivost ve fázi sed-předklon a střední ($\rho > 0.50$) v celé komponentě sed-do-stoje a fázi předklon-stoj.

Při porovnání pacientů s PD s kontrolní skupinou byla maximální hodnota a rozptyl významně odlišné v celé komponentě sed-do-stoje, sed-předklon a předklon-stoj. Průměrná hodnota ukázala rozdíl mezi skupinami ve fázích sed-předklon a předklon-stoj (obrázek 5.3). Doba trvání neprokázala rozdíl mezi skupinami v žádném z testovaných případů.

	Sed-do-stoje				Sed-předklon				Předklon-stoj			
	ρ		PD vs NOR (p-value)		ρ		PD vs NOR (p-value)		ρ		PD vs NOR (p-value)	
Parametr	NOR	PD	TUG1	TUG2	NOR	PD	TUG1	TUG2	NOR	PD	TUG1	TUG2
trvání	0.12	0.40	0.06	0.38	0.17	0.48	0.06	0.42	0.09	0.33	0.14	0.16
maximum	0.42	0.73**	<0.01*	<0.01*	0.43	0.74**	<0.01*	<0.01*	0.53**	0.74**	<0.01*	0.09
průměr	0.30	0.72**	0.80	0.49	0.19	0.39	<0.001*	0.04	0.44	0.53**	<0.001*	0.04*
rozptyl	0.40	0.53**	<0.01*	<0.01*	0.43	0.31	0.01*	<0.01*	0.37	0.70**	0.03*	0.02*

Tabulka 5.2: Výsledky koeficient vnitrotřídní korelace (ρ) a Wilcoxonova rank sum testu pro obě dvě měření testu TUG.

Vysvětlivky: TUG1- první měření testu TUG, TUG2- druhé měření testu TUG, NOR-kontrolní skupina, PD-pacienti s Parkinsonovou chorobou, *-statisticky významný rozdíl, **-střední nebo dobrá úroveň vnitrotřídní korelace

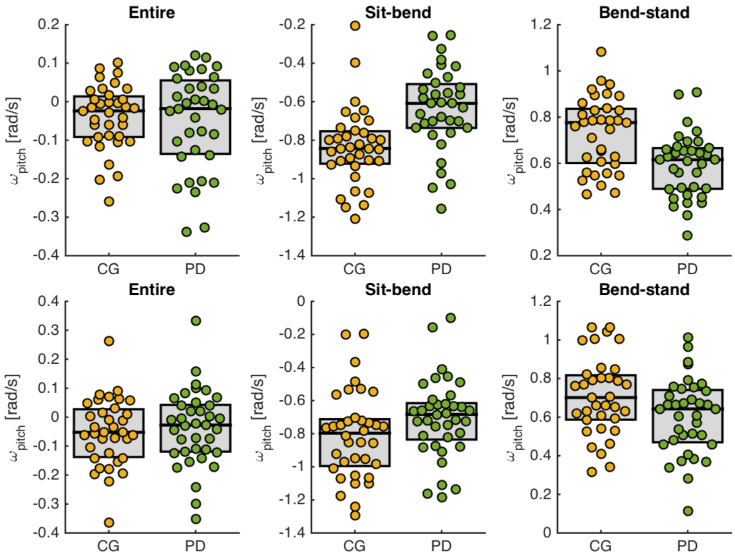
5.2.3 Závěr

Na základě prezentovaných výsledků lze pro kvantitativní analýzu doporučit rozdělení komponenty sed-do-stoje na pod-fáze.

5.2.4 Vlastní publikace

Slavka Viteckova, Radim Krupicka, Petr Dušek, Patrik Kutílek, Zoltán Szabó, Evžen Růžička. Can sit-to-walk assessment maximize instrumented timed up & go test output?. In: Proceedings of the 12th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2019). 12th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2019), Praha, 2019-02-22/2019-02-24. Lisboa: SCITEPRESS – Science and Technology Publications, Lda, 2019. s. 209-213. BIOSIGNALS. sv. 4. ISSN 2184-4305. ISBN 978-989-758-353-7. (konferenční příspěvek publikovaný ve sborníku)

Plný text publikace viz příloha C.



Obrázek 5.3: Bodový graf znázorňující průměr úhlové rychlosti rychlosti pacientů s PD a kontrolní skupiny (NOR) v celé komponentě sed-do-stoje a v pod-fázích sed-předklon a předklon-stoj.

Vysvětlivky: Horní řada grafů reprezentuje první měření testu TUG (TUG1), spodní řada grafů reprezentuje druhé měření testu TUG (TUG2).

Kapitola 6

Komponenta chůze

6.1 Cíl 3: Analýza opakovatelnosti chůzových parametrů při opakovaném měření

Spolehlivé výsledky testu jsou zásadní pro interpretaci a následné přijetí testu do klinické praxe [49]. Proto byla provedena analýza opakovatelnosti parametrů jednotlivých komponent testu TUG za třech podmínek: (1) prostý TUG (TUG), (2) TUG s kognitivní duální úlohou (cTUG) a (3) TUG s manuální duální úlohou (mTUG).

6.1.1 Zpracování

Na základě signálů inerciálních senzorů byly automaticky identifikovány [21] dílčí komponenty prostého testu TUG i jeho kognitivní a manuální varianty. Také chůzové cykly byly detekovány automaticky [21]. Výpočet chůzových parametrů byl založen na dříve publikovaných algoritmech. Časo-prostorové parametry chůze byly vypočteny z úhlové rychlosti v sagitální rovině senzorů umístěných na dolních končetinách [61, 62]. Pohyb paže byl kvantifikován podobně jako v práci Salarian a kol. [21] a Zampieri a kol. [22]. Parametry popisující trup při chůzi byly také určeny v souladu s autory Salarian a kol. [21] a Zampieri a kol. [22]. Parametry trupu při otáčení byly vyhodnoceny ve vertikální ose. Parametry přechodu sed-do-stoje byly odvozeny úhlové rychlosti předklonu [63, 64].

Opakovatelnost parametrů testu TUG byla hodnocena pomocí koeficientu opakovatelnosti (repeatability coefficient, RC) [65]. Před hodnocením opakovatelnosti byl rozdíl mezi měřeními testován párovým t-testem. Hladina významnosti byla nastavena na 0.05. Spolu s koeficientem opakovatelnosti (RC) byl stanoven i jeho 95% interval spolehlivosti. Interval spolehlivosti

95% byl vypočten podle Barnhart a Barborial [66].

Protože opakovatelnost prostřednictvím koeficientu opakovatelnosti je počítána ve stejných jednotkách jako parametry testu TUG, není jeho přímé porovnání napříč parametry, testy (tj. TUG, cTUG, mTUG) nebo skupinami subjektů relevantní. Proto byl pro každý parametr (P) vypočítán poměr parametrů R_P

$$R_P = \frac{RC_P}{mean_P} \tag{6.1}$$

kde RC_P je koeficient opakovatelnosti parametru a $mean_P$ je střední hodnota parametru. Lepší opakovatelnost je indikována nižší hodnotou R_P.

Pro porovnání opakovatelnosti parametrů za různých podmínek, např. napříč skupinami pacientů nebo napříč testy, byl použit úhrnný poměr $R(C1, C2)$, který je počítán jako

$$R(C1, C2) = \frac{R_{P,C1}}{R_{P,C2}} - 1 \tag{6.2}$$

kde $R_{P,C1}$ je poměr parametrů parametru P za podmínky $C1$, např. R_P skupiny PD, a $R_{P,C2}$ je poměr parametrů P za podmínky $C2$, např. R_P skupiny NOR. Pokud se hodnota úhrnného poměru rovná 0, indikuje to rovnost opakovatelnosti při obou podmínkách.

6.1.2 Výsledky

Koeficienty opakovatelnosti spolu s 95% intervaly spolehlivosti pro všechny parametry TUG jsou uvedeny v tabulce 6.1.

Většina chůzových parametrů prostého testu TUG vykazovala v obou skupinách statisticky významné rozdíly mezi prvním a druhým měřením (p<0.05), konkrétně $swing_{max}$, $swing_{RoM}$, $cadence$, t_{GC}, ds, $stride_L$ a $stride_V$. Parametry otáčení vykazovaly obdobné chování pouze ve skupině NOR (p<0.05).

Při manuálním testu TUG vykazovalo v obou skupinách statisticky významný rozdíl mezi měřeními (p<0.05) 8 chůzových parametrů, všechny parametry otáčení a většina parametrů sed-do-stoje ($swing_{max}$, $swing_{RoM}$, $swing_A$, $cadence$, t_{GC}, $stride_V$, $turn_{avg}$, $turn_{max}$, $trunk_{avg}$, $trunk_{max}$, $trunk_{incl}$).

Při analýze kognitivního testu žádný z parametrů neprokázal statisticky významný rozdíl mezi měřeními.

Na základě úhrnného poměru měla většina parametrů u PD ($swing_A$, $cadence$, t_{GC}, ds, $stride_L$, $stride_V$, strideT, var, $stride_{L,var}$, $trunk_{RoM}$, $turn_{avg}$, $trunk_{avg}$, t_{STS}) lepší opakovatelnost při prostém TUG ve srovnání s kognitivním testem. Naproti tomu většina parametrů u NOR ($swing_{max}$, $swing_{RoM}$, $swing_A$, $cadence$, ds, $stride_L$, $stride_V$, $trunk_{RoM}$, $turn_{avg}$, $turn_{max}$,

$trunk_{avg}$, $trunk_{max}$) měla lepší opakovatelnost při kognitivním TUG ve srovnání s prostým testem (tabulka 6.2).

Většina parametrů vykázala v obou skupinách lepší opakovatelnost při manuálním testu než při kognitivním. Pro obě skupiny jsou to tyto parametry: $swing_A$, $cadence$, t_{GC}, $stride_L$, $stride_V$, $stride_{T,var}$, $trunk_{rot,max}$, $trunk_{RoM}$, $trunk_{avg}$ a t_{STS}. Pouze $stride_{L,var}$, $turn_{avg}$ a $trunk_{incl}$ u NOR vykazovaly obdobné chování (tabulka 6.2).

Porovnání opakovatelnosti mezi prostým a manuálním testem ukázalo lepší opakovatelnost u manuálního testu u 13 parametrů ve skupině NOR ($swing_A$, $cadence$, t_{GC}, ds, $stride_L$, $stride_V$, $stride_{L,var}$, $trunk_{RoM}$, $turn_{avg}$, $turn_{max}$, $trunk_{avg}$, t_{STS}, $trunk_{incl}$) a u 8 parametrů ve skupině PD ($swing_A$, $cadence$, t_{GC}, ds, $stride_V$, $turn_{max}$, $trunk_{max}$, $trunk_{incl}$), viz tabulka 6.2.

	TUG		Kognitivní TUG		Manuální TUG	
Parametr	NOR	PD	NOR	PD	NOR	PD
t_T	3.94 (3.09, 5.44)	3.61 (2.83, 4.98)	4.56 (3.58, 6.3)	17.5 (13.7, 24.2)	2.48 (1.95, 3.42)	2.47 (1.94, 3.42)
$swing_{max}$	54.4 (42.6, 75.0)	48.5 (38.1, 67.0)	55.1 (43.2, 76.1)	36.7 (28.7, 50.6)	39.3 (30.8, 54.3)	50.9 (39.9, 70.2)
$swing_{RoM}$	12.4 (9.76, 17.17)	10.4 (8.15, 14.35)	12.6 (9.91, 17.4)	6.31 (4.95, 8.71)	11.3 (8.89, 15.6)	12.9 (10.1, 17.9)
$swing_A$	26.3 (20.6, 36.3)	23.2 (18.2, 32.0)	22.5 (17.7, 31.1)	28.4 (22.3, 39.3)	9.88 (7.75, 13.6)	21.7 (17.0, 30.0)
$cadence$	8.47 (6.64, 11.7)	6.46 (5.06, 8.91)	7.58 (5.94, 10.4)	13.0 (10.2, 18.0)	3.50 (2.74, 4.83)	4.32 (3.39, 5.96)
t_{GC}	0.09 (0.07, 0.13)	0.06 (0.05, 0.09)	0.10 (0.08, 0.13)	0.23 (0.18, 0.31)	0.04 (0.03, 0.05)	0.04 (0.04, 0.06)
ds	2.66 (2.08, 3.67)	5.14 (4.03, 7.09)	1.97 (1.54, 2.72)	7.80 (6.12, 10.76)	2.05 (1.61, 2.83)	4.33 (3.39, 5.97)
$stride_L$	0.08 (0.06, 0.11)	0.07 (0.05, 0.10)	0.07 (0.06, 0.10)	0.12 (0.10, 0.17)	0.05 (0.04, 0.07)	0.07 (0.05, 0.10)
$stride_V$	15.9 (12.5, 22.0)	13.1 (10.3, 18.1)	11.9 (9.37, 16.4)	21.4 (16.8, 29.5)	7.71 (6.05, 10.6)	9.81 (7.7, 13.5)
$stride_{T,var}$	1.57 (1.23, 2.17)	1.31 (1.03, 1.81)	4.14 (3.25, 5.71)	17.8 (14.0, 24.6)	1.92 (1.50, 2.64)	8.76 (6.87, 12.1)
$stride_{L,var}$	2.33 (1.83, 3.22)	2.53 (1.98, 3.49)	3.34 (2.62, 4.61)	6.43 (5.04, 8.87)	1.79 (1.40, 2.46)	6.77 (5.31, 9.34)
$trunk_{rot,max}$	15.8 (12.4, 21.9)	12.2 (9.61, 16.9)	27.6 (21.6, 38.1)	12.8 (10.1, 17.7)	12.2 (9.63, 16.9)	9.9 (7.77, 13.6)
$trunk_{RoM}$	6.77 (5.31, 9.34)	4.10 (3.22, 5.66)	5.90 (4.63, 8.14)	8.10 (6.35, 11.1)	4.05 (3.17, 5.58)	4.48 (3.51, 6.18)
$turn_{avg}$	29.9 (23.4, 41.3)	17.0 (13.3, 23.5)	23.9 (18.8, 33.1)	20.9 (16.4, 28.9)	16.8 (13.2, 23.2)	20.7 (16.2, 28.6)
$turn_{max}$	65.4 (51.3, 90.3)	45.7 (35.8, 63.1)	42.8 (33.5, 59.1)	38.6 (30.2, 53.3)	35.8 (28.1, 49.5)	34.4 (27.0, 47.5)
$trunk_{avg}$	14.8 (11.6, 20.4)	10.6 (8.38, 14.7)	15.4 (12.1, 21.3)	14.2 (11.2, 19.7)	9.58 (7.51, 13.2)	10.3 (8.1, 14.2)
$trunk_{max}$	41.0 (32.1, 56.6)	38.1 (29.9, 52.6)	41.7 (32.7, 57.6)	20.3 (15.9, 28.0)	33.2 (26.0, 45.9)	25.5 (20.0, 35.2)
t_{STS}	0.9 (0.71, 1.25)	0.51 (0.40, 0.71)	1.40 (1.10, 1.94)	16.3 (12.8, 22.5)	0.56 (0.44, 0.78)	0.87 (0.68, 1.20)
$trunk_{incl}$	10.2 (8.05, 14.1)	9.87 (7.74, 13.6)	11.4 (8.95, 15.7)	8.89 (6.97, 12.2)	7.29 (5.72, 10.0)	7.5 (5.88, 10.3)

Tabulka 6.1: Opakovatelnost parametrů za různých podmínek a odpovídající intervaly spolehlivosti (uvedené v závorkách).

	R(TUG, cTUG)		R(TUG,mTUG)		R(cTUG, mTUG)		R(PD, NOR)		
Parametr	NOR	PD	NOR	PD	NOR	PD	TUG	cTUG	mTUG
t_T	-0.10^{TUG}	-0.77^{TUG}	0.61^{mTUG}	0.48^{mTUG}	0.78^{mTUG}	5.45^{mTUG}	-0.07^{PD}	2.67^{NOR}	0.01
$swing_{max}$	0.09^{cTUG}	0.24^{cTUG}	-0.09^{TUG}	-0.39^{TUG}	-0.16^{cTUG}	-0.51^{cTUG}	0.10^{NOR}	-0.04	0.64^{NOR}
$swing_{RoM}$	0.11^{cTUG}	0.61^{cTUG}	-0.18^{TUG}	-0.45^{TUG}	-0.26^{cTUG}	-0.66^{cTUG}	0.12^{NOR}	-0.22^{PD}	0.69^{NOR}
$swing_A$	0.22^{cTUG}	-0.10^{TUG}	7.33^{mTUG}	0.81^{mTUG}	5.85^{mTUG}	1.01^{mTUG}	-0.38^{PD}	-0.16^{PD}	1.87^{NOR}
$cadence$	0.09^{cTUG}	-0.53^{TUG}	1.47^{mTUG}	0.54^{mTUG}	1.28^{mTUG}	2.24^{mTUG}	-0.26^{PD}	0.70^{NOR}	0.19^{NOR}
t_{GC}	-0.07^{TUG}	-0.73^{TUG}	1.21^{mTUG}	0.46^{mTUG}	1.38^{mTUG}	4.35^{mTUG}	-0.32^{PD}	1.31^{NOR}	0.03
ds	0.43^{cTUG}	-0.27^{TUG}	0.28^{mTUG}	0.15^{mTUG}	-0.11^{cTUG}	0.57^{mTUG}	1.16^{NOR}	3.24^{NOR}	1.40^{NOR}
$stride_L$	0.13^{cTUG}	-0.44^{TUG}	0.59^{mTUG}	-0.01	0.41^{mTUG}	0.77^{mTUG}	-0.11^{PD}	0.80^{NOR}	0.43^{NOR}
$stride_V$	0.28^{cTUG}	-0.43^{TUG}	1.11^{mTUG}	0.36^{mTUG}	0.64^{mTUG}	1.40^{mTUG}	-0.19^{PD}	0.84^{NOR}	0.26^{NOR}
$stride_{T,var}$	-0.48^{TUG}	-0.90^{TUG}	-0.17^{TUG}	-0.85^{TUG}	0.59^{mTUG}	0.41^{mTUG}	-0.43^{PD}	1.85^{NOR}	2.19^{NOR}
$stride_{L,var}$	-0.30^{TUG}	-0.61^{TUG}	0.25^{mTUG}	-0.65^{TUG}	0.79^{mTUG}	-0.10^{cTUG}	0.02	0.81^{NOR}	2.62^{NOR}
$trunk_{rot,max}$	-0.40^{TUG}	-0.05	0.04	0.02	0.74^{mTUG}	0.07^{mTUG}	-0.13^{PD}	-0.45^{PD}	-0.11^{PD}
$trunk_{RoM}$	0.20^{cTUG}	-0.46^{TUG}	0.32^{mTUG}	-0.21^{TUG}	0.10^{mTUG}	0.44^{mTUG}	-0.28^{PD}	0.59^{NOR}	0.21^{NOR}
$turn_{avg}$	0.29^{cTUG}	-0.21^{TUG}	0.46^{mTUG}	-0.31^{TUG}	0.13^{mTUG}	-0.14^{cTUG}	-0.35^{PD}	0.05	0.37^{NOR}
$turn_{max}$	0.59^{cTUG}	0.16^{cTUG}	0.50^{mTUG}	0.09^{mTUG}	-0.05	-0.06^{cTUG}	-0.25^{PD}	0.03	0.04
$trunk_{avg}$	0.06^{cTUG}	-0.26^{TUG}	0.13^{mTUG}	-0.20^{TUG}	0.06^{mTUG}	0.09^{mTUG}	-0.13^{PD}	0.25^{NOR}	0.23^{NOR}
$trunk_{max}$	0.15^{cTUG}	0.77^{cTUG}	-0.08^{TUG}	0.15^{mTUG}	-0.20^{cTUG}	-0.35^{cTUG}	0.09^{NOR}	-0.29^{PD}	-0.13^{PD}
t_{STS}	-0.38^{TUG}	-0.96^{TUG}	0.74^{mTUG}	-0.36^{TUG}	1.79^{mTUG}	13.7^{mTUG}	-0.51^{PD}	6.08^{NOR}	0.34^{NOR}
$trunk_{incl}$	-0.04	0.10^{cTUG}	0.22^{mTUG}	0.15^{mTUG}	0.27^{mTUG}	0.04	0.02	-0.12^{PD}	0.08^{NOR}

Tabulka 6.2: Porovnání opakovatelnosti za různých podmínek.

Vysvětlivky: R(TUG, cTUG) - úhrnný poměr parametru při vykonávání testu TUG a kognitivního testu TUG (cTUG); R(TUG,mTUG) - úhrnný poměr parametru při vykonávání testu TUG a manuálního testu TUG (mTUG); R(cTUG,mTUG) - úhrnný poměr parametru při vykonávání kognitivního testu TUG a manuálního testu TUG (mTUG); R(PD, NOR) - úhrnný poměr parametru vykonávaného pacienty s Parkinsonsonovou chorobou (PD) a kontrolní skupiny (NOR); horní index označuje podmínku s lepší opakovatelností

6.1.3 Závěr

Výsledky studií by měly být interpretovány obezřetně s ohledem na počet provedených měření.

6.1.4 Vlastní publikace

Slavka Viteckova, Radim Krupicka, Petr Dusek, Vaclav Cejka, Patrik Kutilek, Jan Novak, Zoltan Szabo, Evžen Růžička. The repeatability of the instrumented Timed Up&Go test: the performance of older adults and Parkinson's disease patients under different conditions, Biocybernetics and Biomedical Engineering, Volume 40. Issue 1, 2020. Pages 363-377, ISSN: 0208-5216 (původní článek, IF 2019 – 2.5)

Plný text publikace viz příloha D.

6.2 Cíl 4: Analýza samostatného hodnocení chůzových komponent před a po otáčení

Hodnocení komponent chůze v testu TUG není standardizováno. Některé studie posuzovaly chůzi před otáčením a chůzi po otáčení samostatně [54], jiné studie kombinovaly obě chůze [37], zatímco většina studií neuvádí, zda je výpočet parametrů chůze založen na kombinaci obou chůzí, např. průměr obou chůzí nebo pouze jeden z nich [55, 28, 31, 32, 49, 23].

6.2.1 Zpracování

Chůze před otočkou a chůze po otočce byly nahrávány samostatně s využitím tlakocitlivého chodníku GAITRite, tj. pro každý TUG byla získána dvě měření. Pro každé měření bylo analyzováno 17 časoprostorových parametrů. Všechna data byla zpracována zkušenou osobou pomocí softwaru GAITRite (verze 4.7). Před statistickým zpracováním byly všechny parametry zprůměrovány z levé a pravé končetiny.

Analyzované parametry jsou výstupem tlakocitlivého chodníku a k němu příslušnému software (tedy v souladu s definicemi výrobce). Tyto parametry jsou: rychlost chůze, počet kroků, kadence, doba trvání kroku, délka kroku, doba trvání chůzového cyklu, délka dvojkroku, šířka opěrné báze, doba trvání švihové fáze, stojné fáze, jednooporové a dvouoporové fáze, percentuální zastoupení doby trvání švihové fáze a oporných fází v chůzovém cyklu, rychlost dvojkroku.

Pro statistické porovnání chůze před a po otočce byl použit párový t-test.

6.2.2 Výsledky

Při srovnání chůze před a po otočce ukázaly výsledky párového t-testu, že rychlost, délka kroku, délka dvou-kroku a percentuální zastoupení fáze dvojí opory vzhledem k trvání chůzového cyklu byly výrazně odlišné u PD ($p<0.002$), ale ne ve skupině NOR. Konkrétně u PD se rychlost chůze snížila a kroky i dvou-kroky se zkrátily po otočce. Mezi chůzí před otočkou a po otočce u NOR neukázal žádný parametr statisticky významný rozdíl (tabulka 6.3).

	Chůze před otáčením		Chůze po otáčení		Rozdíl mezi chůzí před a po otáčení		Srovnání chůze před a po otáčení (p-value)	
Parametr	PD	NOR	PD	NOR	PD	NOR	PD	NOR
Rychlost (cm/s)	111.90 (25.52)	108.90 (14.35)	104.61 (23.55)	105.76 (15.50)	7.29 (6.27)	3.14 (6.07)	**<0.001***	**0.034**
Počet kroků (steps)	5.62 (0.96)	5.80 (0.63)	6.15 (1.07)	6.10 (0.88)	-0.54 (0.66)	-0.30 (0.67)	0.136	0.162
Kadence (steps/min)	109.88 (15.07)	105.79 (8.82)	107.89 (14.37)	106.35 (9.43)	1.99 (4.45)	-0.56 (2.37)	**0.037**	0.465
Trvání kroku (s)	0.56 (0.08)	0.57 (0.05)	0.63 (0.24)	0.57 (0.05)	-0.07 (0.22)	<0.01 (0.02)	0.236	0.302
Délka kroku (cm)	60.45 (7.60)	61.5 (4.75)	57.61 (7.33)	59.48 (4.95)	2.84 (1.51)	2.01 (2.40)	**<0.001***	**0.007**
Trvání cyklu (s)	1.12 (0.16)	1.14 (0.11)	1.19 (0.27)	1.14 (0.10)	-0.07 (0.21)	<0.01 (0.04)	0.187	0.258
Délka dvojkroku (cm)	120.92 (15.12)	123.16 (9.47)	115.44 (14.83)	119.58 (9.96)	5.48 (2.93)	3.58 (4.60)	**<0.001***	**0.007**
Šíře opory (cm)	9.32 (3.02)	10.25 (2.51)	9.98 (2.65)	9.87 (2.69)	-0.66 (1.57)	0.38 (1.03)	0.368	0.112
Švihová fáze (% GC)	37.31 (2.43)	37.10 (2.35)	35.27 (3.56)	36.98 (1.91)	2.04 (3.17)	0.12 (1.82)	**0.008**	0.181
Švihová fáze (s)	0.41 (0.05)	0.42 (0.04)	0.41 (0.04)	0.42 (0.03)	0.01 (0.02)	<0.01 (0.03)	0.071	0.346
Stojná fáze (% GC)	62.71 (2.43)	62.92 (2.35)	64.73 (3.56)	63.03 (1.92)	-2.02 (3.16)	-0.11 (1.82)	**0.007**	0.185
Stojná fáze (s)	0.70 (0.12)	0.72 (0.08)	0.78 (0.24)	0.72 (0.08)	-0.08 (0.21)	<0.01 (0.02)	0.126	0.247
Fáze jedné opory (% GC)	37.37 (2.34)	37.26 (2.02)	35.24 (3.62)	36.96 (1.90)	2.13 (3.16)	0.29 (1.35)	**0.006**	0.172
Fáze jedné opory (s)	0.41 (0.05)	0.42 (0.04)	0.41 (0.04)	0.42 (0.03)	0.01 (0.02)	<0.01 (0.03)	0.071	0.346
Fáze dvojí opory (% GC)	24.73 (4.51)	26.66 (7.98)	28.88 (5.72)	26.45 (3.93)	-4.15 (4.30)	0.21 (7.11)	**0.001***	0.306
Fáze dvojí opory (s)	0.28 (0.09)	0.30 (0.08)	0.36 (0.17)	0.30 (0.07)	-0.08 (0.14)	<0.01 (0.06)	**0.033**	0.234
Rychlost dvojkroku (cm/s)	112.12 (25.27)	108.36 (14.23)	101.86 (25.46)	106.35 (15.49)	10.26 (11.90)	2.01 (5.59)	**0.001***	0.051

Tabulka 6.3: Popisná statistika analyzovaných parametrů (průměr a směrodatná odchylka) a statistické vyhodnocení chůze před otáčením a chůze po otáčení (p-value).

Vysvětlivky: tučně - statisticky významný rozdíl ($p<0.05$), * rozdíly signifikantní po Holm-Bonferroniho korekci (pro 17 testů, $p<0.002$), PD - pacienti s Parkinsonovou chorobou, NOR - kontrolní skupina, GC - chůzový cyklu (gait cycle)

6.2.3 Závěr

Závěrem lze říci, že chůze před otočkou a po otočce se vyznačují různými hodnotami časoprostorových parametrů, a proto by se měly analyzovat a hodnotit odděleně.

6.2.4 Vlastní publikace

Slavka Viteckova, Vaclav Cejka, Petr Dusek, Radim Krupicka, Patrik Kutilek, Zoltan Szabo, Evžen Růžička. Extended Timed Up & Go test: Is walking forward and returning back to the chair equivalent gait?. Journal of Biomechanics. 2019, ISSN 0021-9290. DOI 10.1016/j.jbiomech.2019.04.001.
(krátké sdělení, IF 2019 - 2.3)

Plný text publikace viz příloha E.

Kapitola 7

Komponenta otáčení

7.1 Cíl 5: Rozbor signálů komponenty otáčení vzhledem ke kvantitativní analýze pohybu

Přestože existuje několik parametrů hodnotících otáčení založených na signálech inerciálních senzorů, neexistují žádné informace o opakovatelnosti těchto signálů či o existenci sdíleného vzoru signálů v rámci skupiny subjektů.

7.1.1 Zpracování

Byl proveden rozbor signálu hrudního inerciálního senzoru při vykonávání komponenty otáčení, jmenovitě:

- analýza opakovatelnosti signálu,
- analýza vzoru signálu v rámci skupiny participantů (PD a NOR),
- stanovení predikčního pásma v rámci skupiny participantů (PD a NOR).

Analýza opakovatelnosti signálu téhož participanta při opakovaném měření byla provedena prostřednictvím intraclass correlation coefficient (ICC) [67]. Lze předpokládat, že při opakovaném provádění stejného pohybu jedním participantem bude kinematická křivka téměř shodná. Protože

- jde o porovnání dvou křivek téhož participanta,
- základem pro analýzu je jedno měření (ne průměr z více měření),
- očekáváme téměř shodné křivky,

byla využita varianta ICC dvoucestné smíšené efekty, absolutní shoda, jedno měření.

Vzoru signálu v rámci skupiny participantů byl analyzován pomocí ICC. Na základě předpokladů, že

- měření participantů mají podobné charakteristiky,
- křivky participantů mají stejný vzor plus systematickou chybu,
- základem pro analýzu je jedno měření (ne průměr z více měření),

byla zvolena varianta dvoucestné náhodné efekty, konzistence, jedno měření. ICC bylo počítáno pro každý bod křivky komponenty otáčení.

Predikční pásma byla stanovena použitím dvou metod: bootstrap metodou a Gaussovou metodou bod-po-bodu. Pro počítání pásem metodou bootstrap bylo použito 1000 vzorků. Vlastní implementace metody bootstrap je dostupná na `https://github.com/vitecsla-fbmi/predictionBands/`. Pravděpodobnost skutečného pokrytí u každé ze dvou metod byla stanovena křížovou validací [58].

7.1.2 Výsledky

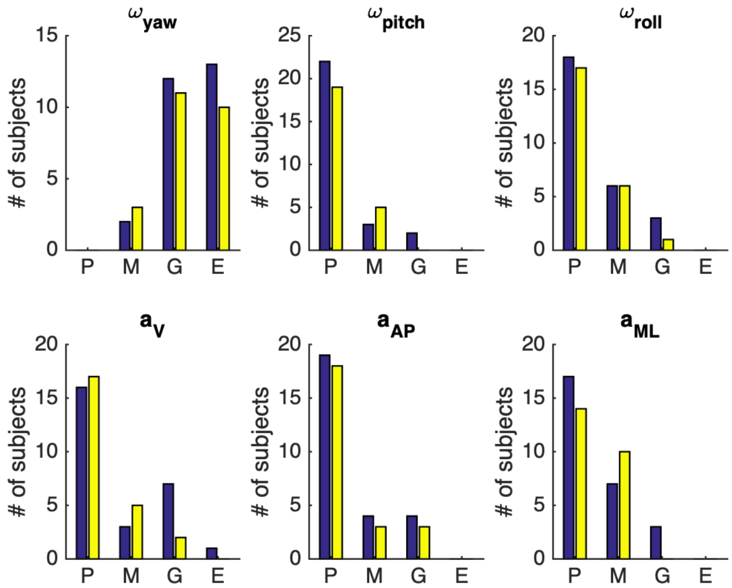
Analýza opakovatelnosti signálu

ICC úhlové rychlosti kolem vertikální osy se pohybuje od střední ($0.50 < \rho < 0.75$) po vynikající ($\rho > 0.90$). Ostatní křivky úhlové rychlosti ukázaly v obou skupinách spolehlivost v rozmezí úrovní od slabé ($\rho < 0.50$) až po dobrou ($0.75 < \rho < 0.90$). Křivky zrychlení podél vertikální osy vykazují u NOR plný rozsah spolehlivosti (od slabých po vynikající) a mírně nižší u PD (od slabých po dobré). U medio-laterálního a antero-posteriorního zrychlení bylo v obou skupinách pozorováno ICC v rozpětí od slabých po dobré. Podrobnosti viz obrázek 7.1.

Analýza vzoru signálu v rámci skupiny

Analýza společného vzoru v signálech zrychlení ukázala v obou skupinách slabou ICC ($\rho < 0.50$).

U úhlové rychlosti se výsledky pohybují v rozmezí od slabé ($\rho < 0.50$) po dobrou ICC ($0.75 < \rho < 0.90$). Nejlepší ICC ukázala úhlová rychlost kolem vertikální osy: $\rho = 0.79$ u PD a $\rho = 0.86$ u NOR. Detaily viz tabulka 7.1.



Obrázek 7.1: Sloupcové grafy spolehlivosti intraindividuálních signálů zrychlení a úhlové rychlosti.
Vysvětlivky: žlutá - PD, modrá - NOR, P-slabé (poor), M-střední (moderate), G-dobré (good), E-vynikající (excelent).

Stanovení predikčního pásma

Šířka predikčního pásma určená metodou bootstrap byla pro všechny kinematické křivky širší než šířka určená Gaussovou metodou bod-po-bodu.

Křížová validace metody bootstrap skupiny NOR u signálu zrychlení ukázala pravděpodobnost pokrytí v rozmezí od 80% do 94% a v rozmezí od 71% do 91% u úhlové rychlosti. U skupiny PD byla pravděpodobnost pokrytí v rozmezí od 80 % do 94 % u zrychlení a od 74 % do 75 % u úhlové rychlosti (tabulka 7.2).

Křížová validace predikčních pásem stanovených metodou bod-po-bodu dosáhla podstatně nižší pravděpodobnosti pokrytí u všech analyzovaných signálů, a to maximálně 40 % (tabulka 7.2).

7.1.3 Závěr

Výše uvedené výsledky ukazují, že úhlová rychlost kolem vertikální osy má nejsilnější společný vzor ze všech analyzovaných signálů v obou vyšetřova-

	a_V	a_{ML}	a_{AP}	ω_{yaw}	ω_{pitch}	ω_{roll}
NOR	0.20	0.07	0.26	0.86*	0.09	0.21
	(0.18-0.24)	(0.05-0.09)	(0.24-0.31)	0(0.84-0.88)	(0.07-0.11)	(0.19-0.25)
PD	0.10	0.01	0.25	0.79*	0.02	0.16
	(0.08-0.12)	(0-0.02)	(0.23-0.3)	(0.77-0.82)	(0.01-0.03)	(0.14-0.2)

Tabulka 7.1: Hodnocení společného vzoru signálů akcelerace a společného vzoru úhlových rychlostí (koeficient vnitrotřídní korelace (ρ) a 95% interval spolehlivosti).
Vysvětlivky: * - dobrá spolehlivost, NOR - kontrolní skupina; PD - pacienti s Parkinsonovou chorobou

		a_V	a_{ML}	a_{AP}	ω_{yaw}	ω_{pitch}	ω_{roll}
NOR	Gaussova	14	31	34	22	8	14
	Bootstrap	80	94	85	91	71	74
PD	Gaussova	14	22	40	31	11	20
	Bootstrap	80	94	88	85	74	85

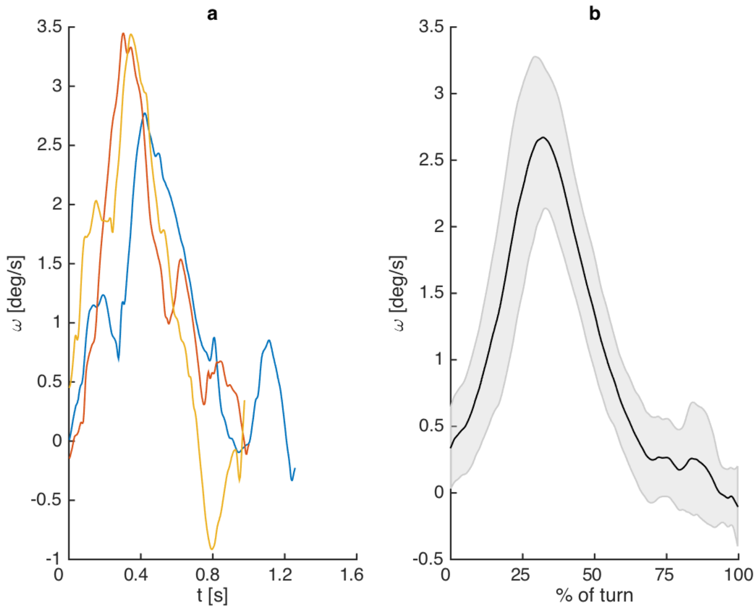
Tabulka 7.2: Pravděpodobnost pokrytí metodou bootstrap a Gaussovou metodou bod-po-bodu (%).
Vysvětlivky: NOR - kontrolní skupina; PD - pacienti s Parkinsonovou chorobou

ných skupinách, tj. PD a NOR. Tento signál dosáhl také nejlepších výsledků při hodnocení opakovatelnosti dvou po sobě jdoucích měřeních jednoho subjektu. Na základě těchto zjištění je možné považovat křivku úhlové rychlosti kolem vertikální osy jako nejvhodnější pro analýzu otáčení.

7.1.4 Vlastní publikace

Slavka Viteckova, Ondrej Klempir, Petr Dusek, Radim Krupicka, Zoltan Szabo, Evžen Růžička. Statistical analysis of the 180 degree walking turn: Common patterns, repeatability and prediction bands of turn signals. Biomedical Signal Processing and Control. 2020, 56 ISSN 1746-8094. DOI 10.1016/j.bspc.2019.101689.
(krátké sdělení, IF 2019 - 3.1)

Plný text publikace viz příloha F.



Obrázek 7.2: Příklady úhlové rychlosti kolem vertikální osy. a) úhlová rychlost tří subjektů, b) průměrný signál všech testovaných subjektů (černá čára) a směrodatná odchylka (šedá) plocha.

7.2 Cíl 6: Návrh přístupu k hodnocení komponenty otáčení zohledňující tvar signálu

Většina studií využívajících inerciální senzory kvantifikuje otáčení pomocí hodnot popisné statistiky, např. průměr nebo maximum signálu. Spolu s rostoucím zájmem o analýzu otáčení během chůze by měly být navrženy nové parametry.

7.2.1 Zpracování

Pro signál úhlové rychlosti hrudního senzoru byl navržen nový parametr popisující tvar signálu - šikmost signálu. Parametr odráží zvonovitý tvar signálu úhlové rychlosti kolem vertikální osy (obrázek 7.2 a jeho odvození vychází ze statistického momentu 3. řádu - šikmosti.

Šikmost signálu, WS (waveform skewness), je vypočítána podle nově navrženého vzorce

$$WS = \frac{\frac{1}{m}\sum_{i=1}^{n}((t_i-\mu)^3\omega_i)}{[\frac{1}{m}\sum_{i=1}^{n}(t_i-\mu)^2\omega_i]^{3/2}}, \tag{7.1}$$

kde $\omega = (\omega_1, , \omega_n)$ je úhlová rychlost, n je délka signálu, t je vektor $[1, 2, , n]$, a m je počet prvků počítaný jako součet prvků úhlové rychlosti, tj.

$$m = \sum_{i=1}^{n} \omega_i, \tag{7.2}$$

a μ je počítáno podle vzorce

$$\mu = \frac{\sum_{i=1}^{n}(\omega_i t_i)}{m}. \tag{7.3}$$

Šikmost signálu charakterizuje jeho asymetrii.

Nově navržený parametr byl srovnáván s již existujícími parametry, jmenovitě to byly tyto parametry: doba trvání otáčení, maximální a průměrná hodnota úhlové rychlosti. Všechny parametry byly testovány za různých okolností - při změně měřítka signálu, časového uspořádání a časového posunu. Dále byla analyzována lineární závislost mezi parametry (korelace) a spolehlivost parametrů (koeficient vnitrotřídní korelace, ICC).

7.2.2 Výsledky

Při analýze vlivu úpravy signálu na parametr, průměr a maximální hodnota vykazovaly významný rozdíl ve výsledcích jako reakci na různá měřítka signálu (p<0.01). Parametry WS, doba trvání a průměr vykazovaly statisticky významný rozdíl pro různé časové posuny (p<0.01).

Druhá analýza hodnotila spolehlivost parametrů. Tato analýza byla provedena pro každou skupinu subjektů samostatně. Doba trvání, průměrná a maximální hodnota signálu prokázaly dobrou spolehlivost u PD ($\rho > 0.75$) a střední spolehlivost u NOR ($\rho > 0.50$). Parametr WS prokázal střední spolehlivost ($\rho > 0.50$) u obou skupin.

Třetí analýza porovnávala parametry vzájemně, jmenovitě jejich korelaci. I v tomto případě byla analýza provedena pro každou skupinu subjektů samostatně. Parametr WS měl středně pozitivní korelaci s průměrnou a maximální hodnotou signálu u NOR (r=0.64 a 0.59, respektive), a slabou pozitivní u PD. Korelace WS a délky trvání byla mírně negativní u NOR (r=-0.57) a nízká negativní u PD (r=-0.37). Maximální hodnota měla středně pozitivní korelaci s hodnotou WS u NOR (r = 0.59) a nízkou pro PD (r=0.47).

Parametr WS ukázal statisticky významný rozdíl (p<0.001) při srovnání obou skupin subjektů.

7.2.3 Závěr

Na základě prezentovaných výsledků lze říci, že nově navržený parametr (WS, waveform skewness) popisující tvar signálu otáčení přináší nový úhel pohledu na hodnocení otáčení při vykonávání testu Timed Up & Go a má potenciál na širší využití v oblasti analýzy otáčení o 180 stupňů.

7.2.4 Vlastní publikace

Slavka Viteckova, Radim Krupicka, Vaclav Cejka, Patrik Kutilek, Zoltan Szabo, Evžen Růžička, Petr Dusek. Waveform skewness: Parameter for timed Up & Go turn assessment. Biomedical Signal Processing and Control. 2019, 52 347-352. ISSN 1746-8094. DOI 10.1016/j.bspc.2019.04.035.
(původní článek, IF 2019 - 3.1)

Plný text publikace viz příloha G.

Kapitola 8

Komponenta otáčení-do-sedu

8.1 Cíl 7: Rozbor signálů komponenty otáčení-před-sedem vzhledem ke kvantitativní analýze pohybu

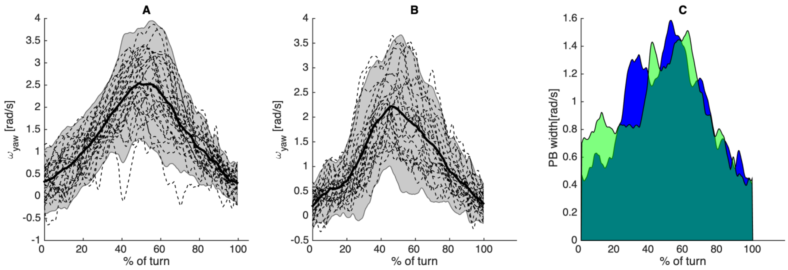
U pacientů s Parkinsonovou chorobou bylo ukázáno prodloužené vykonávání přechodů, např. otáčení-do-sedu [21, 52]. Analýza otáčení před sednutím však není široce používá. Dosud neexistuje studie, která by se zabývala přímým porovnáváním signálů pohybu otáčení-před-sedem.

8.1.1 Zpracování

Pro zpracování pohybu otáčení-před-sedem (počáteční část komponenty otáčení-do-sedu) byla použita úhlová rychlost naměřená hrudním inerciálním senzorem. Z každého měření byla automaticky extrahována komponenta otáčení-před-sedem [21]. K dalšímu zpracování byla použita úhlová rychlost. Vizualizace variability signálů v rámci skupiny byla provedena pomocí predikčního pásma, konkrétně byla použita Gaussova metoda bod-po-bodu. Pro porovnání signálů mezi skupinami byla použita metoda HANOVA [59]. Byl vyhodnocen charakteristický signál analyzovaného pohybu - úhlová rychlost kolem vertikální osy.

8.1.2 Výsledky

Gaussova metoda bod-po-bodu během prvních 25 % obratu ukázala širší predikční pásmo u NOR než u PD (obrázek 8.1). Poté, circa až do poloviny otočky, šířka pásma u PD překročila šířku pásma u NOR. Na závěr pohybu byla šířka pásem u obou skupin byla podobná.



Obrázek 8.1: Úhlová rychlost trupu a predikční pásma otáčení-před-sedem a jejich srovnání.
A: Predikční pásmo kontrolní skupiny (světle šedá - predikční pásmo, tučná křivka - střední hodnota skupiny, přerušované křivky - signály jednotlivých subjektů). B: Predikční pásmo pacientů s Parkinsonovou chorobou (světle šedá - predikční pásmo, tučná křivka - střední hodnota skupiny, přerušované křivky - signály jednotlivých subjektů). C: Srovnání šířky predikčního pásma kontrolní skupiny (zelená) a pacientů s Parkinsonovou chorobou (modrá).

Metoda HANOVA odhalila statisticky významný rozdíl mezi skupinami v signálu pohybu otáčení-před-sedem (p=0.004).

8.1.3 Závěr

Závěrem lze říci, že úhlová rychlost komponenty otáčení-před-sedem je vhodná pro analýzu pohybu pacientů s Parkinsonovou chorobou.

8.1.4 Vlastní publikace

Slavka Viteckova, Radim Krupicka, Petr Dusek, Zoltan Szabo, Patrik Kutilek, Evžen Růžička. Can a turn before sitting have additional value in parkinson disease assessment? Gait & Posture. 2019. Volume 73, Supplement 1, Pages 282-283, ISSN 0966-6362. DOI 10.1016/j.gaitpost.2018.06.209.
(rozšířený abstrakt, IF 2019 - 2.3)

Plný text publikace viz příloha H.

Kapitola 9

Diskuze

V předkládané dizertační práci byla provedena segmentace signálů přístrojového testu TUG na dílčí komponenty testu (sed-do-stoje, chůze před otáčením, otáčení, chůze po otáčení, stoj-do-sedu) s následným rozborem jednotlivých komponent.

Při analýze sdíleného vzoru signálů komponenty sed-do-stoje byly ve skupině NOR pozorovány mírně silnější korelace (spolehlivost) než ve skupině PD, což je v souladu s předchozí studií inerciálních signálů obou skupin [68]. Dále analýza společného vzoru signálů ukázala, že úhlová rychlost předklonu má nejcharakterističtější vzor, což odpovídá intuitivnímu zpracování úhlové rychlosti předklonu v předchozích studiích [52, 13]. Protože úhlová rychlost bočního úklonu ve skupině PD neukázala statisticky významný výsledek a vzorec signálu ve skupině NOR byl zanedbatelný, ale statisticky významný, neočekáváme výrazně silnější vzorec ve skupině PD než ve skupině NOR. Úhlová rychlost kolem vertikální osy neměla u NOR statisticky významný výsledek. Proto by měla být zvážena další analýza.

Na základě výše uvedených pozorování (1) **nedoporučujeme využívání jiného signálu zrychlení než ve směru anteroposterior**, (2) **místo toho doporučujeme použít úhlovou rychlost předklonu**.

Z analýzy diskrétních parametrů pro celou komponentu sed-do-stoje a pro tuto komponentu rozdělenou na 2 fáze (sed-předklon a předklon-stoj) byla zjištěna obdobná spolehlivost v obou případech. Z výsledků lze také odvodit, že **doba trvání celé komponenty sed-do-stoje a jeho fází není vhodná pro hodnocení této komponenty** (celku nebo jejich částí).

Ve skupině PD vykazovaly některé parametry (průměr, rozptyl) nižší spolehlivost ve fázi sed-předklon než v jiných fázích. Na rozdíl od maximální hodnoty jsou průměr a odchylka ovlivněny více přesností detekce komponenty sed-do-stoje. Zejména detekce začátku komponenty sed-do-stoje je náročný úkol, protože fázi sed-předklon může předcházet jemné kývání dopředu a dozadu. Proto by bylo vhodné v budoucí práci **provést porovnání detekčních metod komponenty s ohledem na jejich dopad na počítané parametry**.

Dále jsme testovali, zda parametry vypočítané z jednotlivých fází komponenty dokáží lépe rozlišit mezi PD pacienty a referenční skupinou lépe parametry vypočítané pro celou komponentu. Výsledky této práce jsou v souladu s předchozími studiemi - u diskrétních parametrů doby trvání a průměru signálu vypočítané pro celou komponentu nebyly pozorovány žádné rozdíly mezi skupinami PD a NOR [21, 37]. Průměr signálů však odhalil rozdíl mezi těmito skupinami v obou dílčích fázích (sed-předklon a předklon-stoj). Z provedené analýzy vyplývá, že **rozdělení komponenty na fáze může být přínosem pro analýzu testu TUG**.

Naše zjištění ukázala, že některé prostorové a časové parametry se lišily mezi chůzí vpřed a chůzí zpět a že tyto parametry ovlivňovaly zdravé subjekty a PD pacienty odlišně. Z celkových 17 parametrů žádné parametry u NOR a 5 parametrů u pacientů s PD neprokázaly statisticky významný rozdíl při porovnání chůze mezi před otáčením a chůzí po otáčení. Na základě výsledků se zdá, že **absolutní načasování chůzového cyklu je zachováno, zatímco rozdělení času mezi jednotlivé fáze v rámci chůzového cyklu se u PD liší**.

Axiální rigidita u PD během otáčení může zvýšit laterální nestabilitu [69]. Proto je jedno z možných vysvětlení různých hodnot parametrů při chůzi po otáčení právě zotavení ze stability snížené při otáčení. Dalším vysvětlením může být očekávání přechodu stoj-do-sedu nebo zvýšená únava.

Téměř všechny vyšetřované parametry při provádění prostého testu TUG (bez duální úlohy) ukázaly lepší opakovatelnost u pacientů s PD než u NOR. Naproti tomu v případě duálních testů byla opakovatelnost u NOR lepší než u PD. Toto chování lze přičíst nižší pozornosti u NOR při provádění jediného úkolu, zatímco duální úkoly vyžadují soustředění a následně zvýšily celkovou pozornost test. Také Mancini et al. ukázali podobné trendy, tj. ve srovnání s PD mají NOR nižší opakovatelnost [24].

V některých případech prokázala kontrolní skupina u duálních testů horší opakovatelnost než skupina PD, bylo tomu tak zejména v komponentě sed-do-stoje. To může být ovlivněno mírně vyšším věkem kontrol. Tento vyšší věk by mohl souviset se snížením svalové síly a následně se zvýšenou variabilitou pohybu [70].

Analýza spolehlivosti mezi subjekty ukázala, že v obou vyšetřovaných skupinách (PD, NOR) má úhlová rychlost otáčení kolem vertikální osy nejlépe opakovatelný průběh křivek, tj. nejsilnější společný vzor. Jiné křivky vykazovaly nízkou spolehlivost, což naznačuje, že u nich neexistuje žádná skutečná charakteristika křivek, tj. žádný společný vzor. Proto se tyto křivky nezdají být vhodné pro použití v analýze křivek. Obecně to však neznamená, že tyto křivky nejsou vůbec vhodné pro analýzu otáčení. Po pečlivém výběru mohou tyto křivky sloužit jako základ pro výpočet diskrétních parametrů.

Dále, intraindividuální spolehlivost křivek odkazuje na shodu dvou nebo více křivek od stejného subjektu. Nejvyšší intraindividuální spolehlivost v obou skupinách subjektů byla prokázána u úhlové rychlosti kolem vertikální osy.

Při porovnávání predikčních pásem křivek otáčení pomocí metody bootstrap a gaussovské metody bod-po-bodu, bylo odhaleno výrazně nižší pokrytí při použití gaussovské metody bod-po-bodu, což je v souladu s předchozími studiemi analyzujícími predikční pásma úhlů dolních končetin při chůzi [67], otáčení [71] a kinematiky krční páteře [72]. Ačkoli křivky zrychlení vykazovaly vysoké pokrytí metodou bootstrap, byla pozorována široká šířka pásem predikce. Tyto výsledky poukazují na vysokou variabilitu mezi subjekty v průběhu celého otáčení. Navíc to odpovídá zjištění, že u těchto signálů chybí společný vzor křivky. Na základě toho můžeme odvodit, že tyto křivky nejsou vhodným základem pro rozhodování, zda subjekt patří do určité skupiny nebo ne.

Na základě těchto zjištění je možné považovat **křivku úhlové úhlové rychlosti kolem vertikální osy jako nejvhodnější pro analýzu otáčení**.

Při porovnání spolehlivosti nově navrženého parametru šikmost signálu byla spolehlivost u skupiny NOR nižší než spolehlivost u skupiny PD. Také jiné studie [24, 73] ukázaly podobný trend, kdy NOR měly nižší ICC ve srovnání s PD. Mírná spolehlivost může naznačovat, že parametr odráží přirozenou individualitu provádění otáčení a složitost signálu. Analýza tvaru křivky však může poskytnout vhled do změn pohybového vzorce v čase. Kromě toho Mortanza [74] dospěl k závěru, že časoprostorová analýza chůze není dostatečná a nemůže fungovat jako spolehlivý prediktor pádů u starších osob. **Analýza tvaru křivky otáčení při vykonávání testu TUG může vést k novým poznatkům, a tím k lepšímu porozumění různým patologiím**.

Rychlý nástup používání inerciálních senzorů, pozorovaný v posledních letech, těží ze snadné přenosnosti senzorů i jejich nízkých pořizovacích nákladů (např. ve srovnání s kamerovými systémy). Tyto vlastnosti jsou předpokladem pro využití zařízení pro měření pohybu v ambulantních podmínkách. Tím vzrůstají vyhlídky na použitelnost přístrojového testu Timed Up & Go při určování rizika pádu i mimo oblast výzkumu.

Kapitola 10

Přínos práce v oblasti oboru Biomedicínská a klinická technika

Na základě výše uvedeného lze konstatovat, že významné přínosy předkládané disertační práce v oblasti oboru Biomedicínská a klinická technika s dopadem v oblasti analýzy rizika pádu prostřednictvím testu Timed Up & Go jsou následující zjištění a doporučení:

- nejvhodnější pro analýzu komponenty sed-do-stoje je křivka úhlové rychlosti předklonu
- analýza rozdělené komponenty sed-do-stoje na pod-fáze je ve srovnání s analýzou celé komponenty přínosná
- opakovatelnost jednotlivých parametrů testu TUG je rozdílná, a proto by interpretace výsledků měla být prováděna obezřetně s ohledem na počet provedených měření
- chůze před otočkou a po otočce se vyznačují různými hodnotami časoprostorových parametrů, a proto by se měly analyzovat a hodnotit odděleně
- nejvhodnější pro analýzu komponenty otáčení je křivka úhlové rychlosti kolem vertikální osy
- nově navržený parametr popisující tvar celého signálu otáčení přináší nový úhel pohledu na hodnocení komponenty otáčení
- křivky úhlové rychlosti vybočení komponenty sed-do-stoje by měly být podrobeny detailnější analýze
- úhlová rychlost komponenty otáčení-před-sedem by měly být podrobněji analýzovány.

Kapitola 11

Závěr

Pro naplnění cílů dizertační práce byly analyzovány všechny komponenty testu Timed Up & Go: sed-do-stoje, chůze, otáčení, stoj-do-sedu. Byl proveden rozbor signálů inerciálních senzorů pro komponenty sed-do-stoje a otáčení. Při rozboru byla zkoumána hlavně jejich opakovatelnost a sdílený vzor signálů. U komponenty sed-do-stoje byla navíc posuzována výhodnost rozdělení komponenty na fáze. Pro komponentu otáčení byl navržen nový parameter, který uvažuje celý signál a hodnotí jeho tvar. U komponenty chůze bylo provedeno srovnání opakovatelnosti parametru mezi 3 variantami testu, jmenovitě prostého testu, testu s manuální duální úlohou a testu s kognitivní duální úlohou. Dále byl statisticky hodnocen rozdíl v chůzových parametrech při chůzi před otáčením a chůzi po otáčení. Analýza jednotlivých komponent testu je klíčová pro návrh nových parametrů, pro větší rozšíření přístrojového testu ve výzkumu i před následným přijetím do klinické praxe.

Kapitola 12

Seznam významných publikací autorky

12.1 Publikace použité v dizertační práci

12.1.1 Publikace v časopisech s impakt faktorem

Slavka Viteckova, Vaclav Cejka, Petr Dusek, Radim Krupicka, Patrik Kutilek, Zoltan Szabo, Evžen Růžička. Extended Timed Up & Go test: Is walking forward and returning back to the chair equivalent gait?. Journal of Biomechanics. 2019, ISSN 0021-9290. DOI 10.1016/j.jbiomech.2019.04.001.
(krátké sdělení, IF 2019 - 2.3)

Slavka Viteckova, Radim Krupicka, Petr Dusek, Vaclav Cejka, Patrik Kutilek, Jan Novak, Zoltan Szabo, Evžen Růžička. The repeatability of the instrumented Timed Up&Go test: the performance of older adults and Parkinson's disease patients under different conditions, Biocybernetics and Biomedical Engineering, Volume 40, Issue 1, 2020, Pages 363-377, ISSN: 0208-5216
(původní článek, IF 2019 – 2.5)

Slavka Viteckova, Ondrej Klempir, Petr Dusek, Radim Krupicka, Zoltan Szabo, Evžen Růžička. Statistical analysis of the 180 degree walking turn: Common patterns, repeatability and prediction bands of turn signals. Biomedical Signal Processing and Control. 2020, 56 ISSN 1746-8094. DOI 10.1016/j.bspc.2019.101689.
(krátké sdělení, IF 2019 - 3.1)

Slavka Viteckova, Radim Krupicka, Vaclav Cejka, Patrik Kutilek, Zoltan Szabo, Evžen Růžička, Petr Dusek. Waveform skewness: Parameter for timed Up & Go turn assessment. Biomedical Signal Processing and Control. 2019, 52 347-352. ISSN 1746-8094. DOI 10.1016/j.bspc.2019.04.035.
(původní článek, IF 2019 - 3.1)

Slavka Viteckova, Radim Krupicka, Petr Dusek, Zoltan Szabo, Patrik Kutilek, Evžen Růžička. Can a turn before sitting have additional value in parkinson disease assessment? Gait & Posture. 2019. Volume 73, Supplement 1, Pages 282-283, ISSN 0966-6362. DOI 10.1016/j.gaitpost.2018.06.209.
(rozšířený abstrakt, IF 2019 - 2.3)

12.1.2 Publikace ve sbornících

Slavka Viteckova, Radim Krupicka, Petr Dušek, Patrik Kutílek, Zoltán Szabó, Evžen Růžička. Can sit-to-walk assessment maximize instrumented timed up & go test output?. In: Proceedings of the 12th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2019). 12th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2019), Praha, 2019-02-22/2019-02-24. Lisboa: SCITEPRESS – Science and Technology Publications, Lda, 2019. s. 209-213. BIOSIGNALS. sv. 4. ISSN 2184-4305. ISBN 978-989-758-353-7.

12.1.3 Publikace v recenzním řízení

Slavka Netukova, Ondrej Klempir, Radim Krupicka, Petr Dusek, Patrik Kutilek, Zoltan Szabo, Evžen Růžička. The Timed Up & Go test sit-to-stand transition: which signals measured by inertial sensors are viable route for continuous analysis?.
(v recenzním řízení)

12.2 Ostatní publikace relevantní k analýze chůze

12.2.1 Publikace v časopisech s impakt faktorem

Slávka Vítečková, Hana Horáková, Kamila Poláková, Radim Krupička, Evžen Růžička, Hana Brožová. Agreement between the GAITRite® System

and the Wearable Sensor BTS G-Walk® for measurement of gait parameters in healthy adults and Parkinson's disease patients. PeerJ. 2020;8:e8835. Published 2020 May 22. doi:10.7717/peerj.8835
(původní článek, IF 2019 - 2.4)

Slavka Viteckova, Jan Rusz, Radim Krupicka, Petr Dusek, Evžen Růžička. Instrumental Analysis of Gait Abnormalities in Idiopathic Rapid Eye Movement Sleep Behavior Disorder, Movement Disorders, 35: 193-195, ISSN 1531-8257. DOI:10.1002/mds.27938.
(letter to editor, IF 2019 - 8.6)

Dragana Žarković, Monika Šorfová, James J Tufano, Patrik Kutílek, **Slávka Vítečková**, Katja Groleger-Sršen, David Ravnik. Effect of Robot-Assisted Gait Training on Selective Voluntary Motor Control in Ambulatory Children with Cerebral Palsy. Indian Pediatrics. 2020 May. (v tisku) (research letter, IF 2019 - 1.2)

Slavka Viteckova, Siddhartha Khandelwal, Patrik Kutilek, Radim Krupicka, Zoltan Szabo. Gait symmetry methods: Comparison of waveform-based Methods and recommendation for use. Biomedical Signal Processing and Control. 2020, 55 ISSN 1746-8094. DOI 10.1016/j.bspc.2019.101643.
(původní článek, IF 2019 - 3.1)

Slavka Viteckova, Patrik Kutilek, Zdenek Svoboda, Radim Krupicka, Jan Kauler, Zoltan Szabo. Gait symmetry measures: A review of current and prospective methods. Biomedical Signal Processing and Control. 2018, 42 89-100. ISSN 1746-8094. DOI 10.1016/j.bspc.2018.01.013.
(rešeršní článek, IF 2018 - 2.9)

Slavka Viteckova, Radim Krupicka, Zoltan Szabo, Patrik Kutilek, Martina Hoskovcova, Evžen Růžička. P 056 - The effect of medication on walking turns in Parkinson disease. Gait & Posture. 2018, 65 325-326. ISSN 0966-6362. DOI 10.1016/j.gaitpost.2018.06.209.
(rozšířený abstrakt, IF 2018 - 2.4)

12.2.2 Publikace ve sbornících a abstrakty

Slavka Viteckova, Patrik Kutilek, Jana Lenartova, Jana Kopecka, Daniela Mullerova, Radim Krupicka. Evaluation of movement of patients with Parkinson's disease using accelerometers and method based on eigenvectors. In: MAGA, D., A. ŠTEFEK a T. BŘEZINA, eds. Proceedings of the 2016 17th International Conference on Mechatronics - Mechatronika (ME) 2016. Mechatronika, Praha, 2016-12-07/2016-12-09. Prague: Czech Technical University in Prague, Faculty of Electrical Engineering, 2016. s. 61-65. ISBN 978-80-01-05883-1.

Slavka Viteckova, Patrik Kutilek, Radim Krupicka, Barbora Adamova, Zoltan Szabo, Ana Carolina DAngeles Mendes de Brito, Jana Kopecka. Evaluation of movement of patients with Parkinson's disease using wearable MoCap system and bilateral cyclograms. In: 2017 International Conference on Applied Electronics. 22nd International Conference Applied Electronics 2017, Pilsen, 2017-09-05/2017-09-06. Pilsen: University of West Bohemia, 2017. s. 61-65. ISSN 1803-7232. ISBN 978-80-261-0641-8. DOI 10.23919/AE.2017.8053628.

Literatura

[1] L. D. Gillespie, M. C. Robertson, W. J. Gillespie, C. Sherrington, S. Gates, L. M. Clemson, and S. E. Lamb, “Interventions for preventing falls in older people living in the community,” *The Cochrane database of systematic reviews*, pp. CD007146–CD007146, 09 2012.

[2] C. McKay and K. E. Anderson, “How to manage falls in community dwelling older adults: a review of the evidence,” *Postgraduate medical journal*, vol. 86, pp. 299–306, 05 2010.

[3] P. Scuffham, S. Chaplin, and R. Legood, “Incidence and costs of unintentional falls in older people in the united kingdom,” *Journal of Epidemiology & Community Health*, vol. 57, no. 9, pp. 740–744, 2003.

[4] S. Mathias, U. S. L. Nayak, and B. Isaacs, “Balance in Elderly Patients: The “Get-up and Go” Test,” *Archives of Physical Medicine and Rehabilitation*, vol. 34, pp. 119–126, 1986.

[5] A. G. S. Panel on Prevention of Falls in Older Persons and B. G. Society, “Summary of the updated american geriatrics society/british geriatrics society clinical practice guideline for prevention of falls in older persons,” *Journal of the American Geriatrics Society*, vol. 59, pp. 148–157, 01 2011.

[6] C. for Clinical Practice at NICE (UK), *Falls: Assessment and Prevention of Falls in Older People*. National Institute for Health and Care Excellence:, London, Jun 2013.

[7] A. Dubois, T. Bihl, and J.-P. Bresciani, “Automating the Timed Up and Go Test Using a Depth Camera,” *Sensors (Basel, Switzerland)*, vol. 18, no. 1, p. 14, 2017.

[8] T. Li, J. Chen, C. Hu, Y. Ma, Z. Wu, W. Wan, Y. Huang, F. Jia, C. Gong, S. Wan, and L. Li, "Automatic timed up-and-go sub-task segmentation for parkinson's disease patients using video-based activity classification," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, pp. 2189–2199, Nov 2018.

[9] S. Mellone, C. Tacconi, and L. Chiari, "Validity of a smartphone-based instrumented timed up and go," *Gait & Posture*, vol. 36, no. 1, pp. 163 – 165, 2012.

[10] M. R. Narayanan, S. R. Lord, M. M. Budge, B. G. Celler, and N. H. Lovell, "Falls management: Detection and prevention, using a waist-mounted triaxial accelerometer," in *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4037–4040, Aug 2007.

[11] M. R. Narayanan, M. E. Scalzi, S. J. Redmond, S. R. Lord, B. G. Celler, and N. H. Lovell, "A wearable triaxial accelerometry system for longitudinal assessment of falls risk," in *2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 2840–2843, Aug 2008.

[12] M. R. Narayanan, S. J. Redmond, M. E. Scalzi, S. R. Lord, B. G. Celler, and N. H. Lovell *, "Longitudinal falls-risk estimation using triaxial accelerometry," *IEEE Transactions on Biomedical Engineering*, vol. 57, pp. 534–541, March 2010.

[13] Y. Higashi, K. Yamakoshi, T. Fujimoto, M. Sekine, and T. Tamura, "Quantitative evaluation of movement using the timed up-and-go test," *IEEE Engineering in Medicine and Biology Magazine*, vol. 27, pp. 38–46, jul 2008.

[14] S. Gillain, E. Warzee, F. Lekeu, V. Wojtasik, D. Maquet, J.-L. Croisier, E. Salmon, and J. Petermans, "The value of instrumental gait analysis in elderly healthy, {MCI} or Alzheimer's disease subjects and a comparison with other clinical tests used in single and dual-task conditions," *Annals of Physical and Rehabilitation Medicine*, vol. 52, no. 6, pp. 453–474, 2009.

[15] M. Marschollek, K. Wolf, M. Gietzelt, G. Nemitz, H. Meyer zu Schwabedissen, and R. Haux, "Assessing elderly persons' fall risk using spectral analysis on accelerometric data - a clinical evaluation study," in *2008*

30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 3682–3685, Aug 2008.

[16] M. Marschollek, G. Nemitz, M. Gietzelt, K. Wolf, H. Meyer zu Schwabedissen, and R. Haux, "Prädiktion von stürzen stationärer patienten in einer geriatrischen klinik," *Zeitschrift für Gerontologie und Geriatrie*, vol. 42, pp. 317–322, Aug 2009.

[17] B. R. Greene, A. O'Donovan, R. Romero-Ortuno, L. Cogan, C. N. Scanaill, and R. A. Kenny, "Quantitative Falls Risk Assessment Using the Timed Up and Go Test," *IEEE Transactions on Biomedical Engineering*, vol. 57, pp. 2918–2926, dec 2010.

[18] L. Palmerini, S. Mellone, G. Avanzolini, F. Valzania, and L. Chiari, "Quantification of motor impairment in parkinson's disease using an instrumented timed up and go test," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 21, pp. 664–673, July 2013.

[19] D. Vervoort, N. Vuillerme, N. Kosse, T. Hortobágyi, and C. J. C. Lamoth, "Multivariate analyses and classification of inertial sensor data to identify aging effects on the timed-Up-and-Go test," *PLoS ONE*, vol. 11, no. 6, 2016.

[20] R. C. King, L. Atallah, C. Wong, F. Miskelly, and G. Yang, "Elderly risk assessment of falls with bsn," in *2010 International Conference on Body Sensor Networks*, pp. 30–35, June 2010.

[21] A. Salarian, F. B. Horak, C. Zampieri, P. Carlson-Kuhta, J. G. Nutt, and K. Aminian, "ITUG, a sensitive and reliable measure of mobility," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 3, pp. 303–310, 2010.

[22] C. Zampieri, A. Salarian, P. Carlson-Kuhta, K. Aminian, J. G. Nutt, and F. B. Horak, "The instrumented timed up and go test: potential outcome measure for disease modifying therapies in parkinson's disease," *Journal of neurology, neurosurgery, and psychiatry*, vol. 81, pp. 171–176, 02 2010.

[23] R. I. Spain, R. J. George, A. Salarian, M. Mancini, J. M. Wagner, F. B. Horak, and D. Bourdette, "Body-worn motion sensors detect balance and gait deficits in people with multiple sclerosis who have normal walking speed," *Gait & posture*, vol. 35, no. 4, pp. 573–578, 2012.

[24] M. Mancini, A. Salarian, P. Carlson-Kuhta, C. Zampieri, L. King, L. Chiari, and F. B. Horak, “ISway: a sensitive, valid and reliable measure of postural control,” *Journal of NeuroEngineering and Rehabilitation*, vol. 9, p. 59, aug 2012.

[25] J. T. Coulthard, T. T. Treen, A. R. Oates, and J. L. Lanovaz, “Evaluation of an inertial sensor system for analysis of timed-up-and-go under dual-task demands,” *Gait & Posture*, vol. 41, no. 4, pp. 882 – 887, 2015.

[26] S. K. Sankarpandi, A. J. Baldwin, J. Ray, and C. Mazzà, “Reliability of inertial sensors in the assessment of patients with vestibular disorders: a feasibility study,” *BMC ear, nose, and throat disorders*, vol. 17, pp. 1; 1–1, 02 2017.

[27] R. B. Sample, A. L. Kinney, K. Jackson, W. Diestelkamp, and K. E. Bigelow, “Identification of key outcome measures when using the instrumented timed up and go and/or posturography for fall screening,” *Gait & Posture*, vol. 57, pp. 168–171, 2017.

[28] J. J. Craig, A. P. Bruetsch, S. G. Lynch, F. B. Horak, and J. M. Huisinga, “Instrumented balance and walking assessments in persons with multiple sclerosis show strong test-retest reliability,” *Journal of NeuroEngineering and Rehabilitation*, vol. 14, p. 43, 2017.

[29] M. A. Newman, M. A. Hirsch, R. D. Peindl, N. A. Habet, T. J. Tsai, M. S. Runyon, T. Huynh, and N. Zheng, “Reliability of the subcomponents of the instrumented timed up and go test in ambulatory children with traumatic brain injury and typically developed controls,” *Gait & Posture*, vol. 63, pp. 248–253, jun 2018.

[30] L. Hershkovitz, O. Malcay, Y. Grinberg, S. Berkowitz, and A. Kalron, “The contribution of the instrumented timed-up-and-go test to detect falls and fear of falling in people with multiple sclerosis,” *Multiple Sclerosis and Related Disorders*, vol. 27, pp. 226 – 231, 2019.

[31] B. R. Greene, E. P. Doheny, C. Walsh, C. Cunningham, L. Crosby, and R. A. Kenny, “Evaluation of Falls Risk in Community-Dwelling Older Adults Using Body-Worn Sensors,” *Gerontology*, vol. 58, no. 5, pp. 472–480, 2012.

[32] K. J. Sheehan, B. R. Greene, C. Cunningham, L. Crosby, and R. A. Kenny, “Early identification of declining balance in higher functioning

older adults, an inertial sensor based method," *Gait & Posture*, vol. 39, no. 4, pp. 1034–1039, 2014.

[33] D. McGrath, B. R. Greene, E. P. Doheny, D. J. McKeown, G. De Vito, and B. Caulfield, "Reliability of quantitative tug measures of mobility for use in falls risk assessment," in *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 466–469, 2011.

[34] E. Smith, L. Walsh, J. Doyle, B. Greene, and C. Blake, "Effect of a dual task on quantitative timed up and go performance in community-dwelling older adults: A preliminary study," *Geriatrics & Gerontology International*, vol. 17, no. 8, pp. 1176–1182, 2017.

[35] B. R. Greene, B. Caulfield, D. Lamichhane, W. Bond, J. Svendsen, C. Zurski, and D. Pratt, "Longitudinal assessment of falls in patients with parkinson's disease using inertial sensors and the timed up and go test," *Journal of Rehabilitation and Assistive Technologies Engineering*, vol. 5, p. 2055668317750811, 2018.

[36] A. Weiss, T. Herman, M. Plotnik, M. Brozgol, I. Maidan, N. Giladi, T. Gurevich, and J. M. Hausdorff, "Can an accelerometer enhance the utility of the timed up & go test when evaluating patients with parkinson's disease?," *Medical Engineering & Physics*, vol. 32, no. 2, pp. 119 – 125, 2010.

[37] A. Weiss, A. Mirelman, A. S. Buchman, D. A. Bennett, and J. M. Hausdorff, "Using a body-fixed sensor to identify subclinical gait difficulties in older adults with iadl disability: Maximizing the output of the timed up and go," *PLOS ONE*, vol. 8, pp. 1–8, 07 2013.

[38] R. Moe-Nilssen and J. L. Helbostad, "Estimation of gait cycle characteristics by trunk accelerometry," *Journal of Biomechanics*, vol. 37, no. 1, pp. 121–126, 2004.

[39] A. I. Cuesta-Vargas, C. Cano-Herrera, D. Formosa, and B. Burkett, "Electromyographic responses during time get up and go test in water (wtug)," *SpringerPlus*, vol. 2, pp. 217; 217–217, 05 2013.

[40] B. Mariani, M. C. Jiménez, F. J. G. Vingerhoets, and K. Aminian, "On-shoe wearable sensors for gait and turning assessment of patients with parkinson's disease," *IEEE Transactions on Biomedical Engineering*, vol. 60, pp. 155–158, Jan 2013.

[41] B. Najafi, D. G. Armstrong, and J. Mohler, "Novel wearable technology for assessing spontaneous daily physical activity and risk of falling in older adults with diabetes," *Journal of diabetes science and technology*, vol. 7, pp. 1147–1160, 09 2013.

[42] C. Strohrmann, R. Labruyère, C. N. Gerber, H. J. van Hedel, B. Arnrich, and G. Tröster, "Monitoring motor capacity changes of children during rehabilitation using body-worn sensors," *Journal of NeuroEngineering and Rehabilitation*, vol. 10, p. 83, Jul 2013.

[43] T. Tmaura, N. A. Zakaria, Y. Kuwae, M. Sekine, K. Minato, and M. Yoshida, "Quantitative analysis of the fall-risk assessment test with wearable inertia sensors," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 7217–7220, July 2013.

[44] N. A. Zakaria, Y. Kuwae, T. Tamura, K. Minato, and S. Kanaya, "Quantitative analysis of fall risk using TUG test," *Computer Methods in Biomechanics and Biomedical Engineering*, 2015.

[45] S. K. SankarPandi, S. Dlay, W. L. Woo, and M. Catt, "Predicting disability levels of community dwelling older individuals using single wrist mounted accelerometer," in *IEEE-EMBS International Conference on Biomedical and Health Informatics (BHI)*, pp. 720–723, June 2014.

[46] M. Ponti, P. Bet, C. L. Oliveira, and P. C. Castro, "Better than counting seconds: Identifying fallers among healthy elderly using fusion of accelerometer features and dual-task timed up and go," *PloS one*, vol. 12, pp. e0175559; e0175559–e0175559, 04 2017.

[47] H. J. Witchel, C. Oberndorfer, R. Needham, A. Healy, C. E. I. Westling, J. H. Guppy, J. Bush, J. Barth, C. Herberz, D. Roggen, B. M. Eskofier, W. Rashid, N. Chockalingam, and J. Klucken, "Thigh-derived inertial sensor metrics to assess the sit-to-stand and stand-to-sit transitions in the timed up and go (tug) task for quantifying mobility impairment in multiple sclerosis," *Frontiers in Neurology*, vol. 9, p. 684, 2018.

[48] A. Caronni, I. Sterpi, P. Antoniotti, E. Aristidou, F. Nicolaci, M. Picardi, G. Pintavalle, V. Redaelli, G. Achille, L. Sciumè, and M. Corbo, "Criterion validity of the instrumented timed up and go test: A partial least square regression study," *Gait & Posture*, vol. 61, pp. 287 – 293, 2018.

[49] E. Smith, L. Walsh, J. Doyle, B. Greene, and C. Blake, "The reliability of the quantitative timed up and go test (QTUG) measured over five consecutive days under single and dual-task conditions in community dwelling older adults," *Gait & Posture*, vol. 43, pp. 239–244, 2016.

[50] A. Galán-Mercant and A. I. Cuesta-Vargas, "Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks," *BMC Research Notes*, 2014.

[51] N. Millor, P. Lecumberri, M. Gomez, A. Mart\'\inez-Ramirez, and M. Izquierdo, "Kinematic Parameters to Evaluate Functional Performance of Sit-to-Stand and Stand-to-Sit Transitions Using Motion Sensor Devices: A Systematic Review," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, pp. 926–936, sep 2014.

[52] N. A. Zakaria, Y. Kuwae, T. Tamura, K. Minato, and S. Kanaya, "Quantitative analysis of fall risk using TUG test," *Computer Methods in Biomechanics and Biomedical Engineering*, 2015.

[53] A. Sant'Anna and N. Wickström, "A Symbol-Based Approach to Gait Analysis From Acceleration Signals: Identification and Detection of Gait Events and a New Measure of Gait Symmetry," *IEEE Transactions on Information Technology in Biomedicine*, vol. 14, pp. 1180–1187, sep 2010.

[54] J. H. Ansai, L. P. de Andrade, T. H. Nakagawa, and J. R. Rebelatto, "Performances on the Timed Up and Go Test and subtasks between fallers and non-fallers in older adults with cognitive impairment," *Arquivos de Neuro-Psiquiatria*, vol. 76, pp. 381–386, 2018.

[55] G. Adusumilli, S. Lancia, V. A. Levasseur, V. Amblee, M. Orchard, J. M. Wagner, and R. T. Naismith, "Turning is an important marker of balance confidence and walking limitation in persons with multiple sclerosis," *PLOS ONE*, vol. 13, no. 6, pp. 1–10, 2018.

[56] M. Hoskovcová, P. Dušek, T. Sieger, H. Brožová, K. rina Zárubová, O. rej Bezd\'\iček, O. Šprdl\'\ik, R. Jech, J. Štochl, J. Roth, and E. R\r užička, "Predicting Falls in Parkinson Disease: What Is the Value of Instrumented Testing in OFF Medication State?," *PLOS ONE*, vol. 10, no. 10, pp. 1–13, 2015.

[57] J. Wall, C. Bell, S. Campbell, and J. Davis, "The Timed Get-up-and-Go test revisited: Measurement of the component tasks," *J Rehabil Res Dev*, vol. 37, pp. 109–113, 2000.

[58] M. W. Lenhoff, T. J. Santner, J. C. Otis, M. G. E. Peterson, B. J. Williams, and S. I. Backus, “Bootstrap prediction and confidence bands: a superior statistical method for analysis of gait data,” *Gait & Posture*, vol. 9, no. 1, pp. 10–17, 1999.

[59] T. Chau, S. Young, and S. Redekop, “Managing variability in the summary and comparison of gait data,” *Journal of NeuroEngineering and Rehabilitation*, vol. 2, p. 22, 2005.

[60] A. Galán-Mercant and A. I. Cuesta-Vargas, “Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks,” *BMC Research Notes*, 2014.

[61] A. Salarian, H. Russmann, F. J. G. Vingerhoets, C. Dehollain, Y. Blanc, P. R. Burkhard, and K. Aminian, “Gait assessment in Parkinson’s disease: toward an ambulatory system for long-term monitoring,” *IEEE Transactions on Biomedical Engineering*, vol. 51, pp. 1434–1443, aug 2004.

[62] S. T. Moore, H. G. MacDougall, J.-M. Gracies, H. S. Cohen, and W. G. Ondo, “Long-term monitoring of gait in Parkinson’s disease,” *Gait & Posture*, vol. 26, no. 2, pp. 200–207, 2007.

[63] B. Najafi, K. Aminian, F. Loew, Y. Blanc, and P. A. Robert, “Measurement of stand-sit and sit-stand transitions using a miniature gyroscope and its application in fall risk evaluation in the elderly,” *IEEE Transactions on Biomedical Engineering*, vol. 49, pp. 843–851, aug 2002.

[64] A. Salarian, H. Russmann, F. J. G. Vingerhoets, P. R. Burkhard, and K. Aminian, “Ambulatory Monitoring of Physical Activities in Patients With Parkinson’s Disease,” *IEEE Transactions on Biomedical Engineering*, vol. 54, pp. 2296–2299, dec 2007.

[65] J. M. Bland and D. Altman, “STATISTICAL METHODS FOR ASSESSING AGREEMENT BETWEEN TWO METHODS OF CLINICAL MEASUREMENT,” *The Lancet*, vol. 327, no. 8476, pp. 307–310, 1986.

[66] H. X. Barnhart and D. P. Barboriak, “Applications of the Repeatability of Quantitative Imaging Biomarkers: A Review of Statistical Analysis of Repeat Data Sets,” *Translational Oncology*, vol. 2, no. 4, pp. 231–235, 2009.

[67] A. Duhamel, J. L. Bourriez, P. Devos, P. Krystkowiak, A. Destée, P. Derambure, and L. Defebvre, “Statistical tools for clinical gait analysis,” *Gait & Posture*, vol. 20, no. 2, pp. 204–212, 2004.

[68] S. Viteckova, O. Klempir, P. Dusek, R. Krupicka, Z. Szabo, and E. R\r užička, “Statistical analysis of the 180 degree walking turn: Common patterns, repeatability and prediction bands of turn signals,” *Biomedical Signal Processing and Control*, vol. 56, 2020.

[69] W.-C. Yang, W.-L. Hsu, R.-M. Wu, and K.-H. Lin, “Immediate effects of clock-turn strategy on the pattern and performance of narrow turning in persons with Parkinson disease,” *Journal of Neurologic Physical Therapy*, vol. 40, no. 4, pp. 249–256, 2016.

[70] H. G. Kang and J. B. Dingwell, “Separating the effects of age and walking speed on gait variability,” *Gait & Posture*, vol. 27, no. 4, pp. 572–577, 2008.

[71] P. C. Dixon, J. Stebbins, T. Theologis, and A. B. Zavatsky, “Spatio-temporal parameters and lower-limb kinematics of turning gait in typically developing children,” *Gait and Posture*, vol. 38, no. 4, pp. 870–875, 2013.

[72] W. J. Anderst, “Bootstrap prediction bands for cervical spine intervertebral kinematics during in vivo three-dimensional head movements,” *Journal of Biomechanics*, vol. 48, no. 7, pp. 1270–1276, 2015.

[73] S. Viteckova, R. Krupicka, P. Kutilek, V. Cejka, Z. Szabo, M. Hoskovcova, and E. Ruzicka, “Wave kurtosis: A novel, specific parameter for TUG-Turn quantification,” in *IFMBE Proceedings*, vol. 68, pp. 339–343, 2018.

[74] N. Mortaza, N. A. A. Osman, and M. Mehdikhani, “Are the Spatio-temporal Parameters of Gait Capable of Distinguishing a Faller from a Non-faller Elderly?,” *European Journal of Physical and Rehabilitation Medicine*, vol. 50, no. 6, pp. 677–691, 2014.

PŘÍLOHY

Příloha A

Zpracování signálů otáčení o 180°

A.1 Introduction

Turning is an essential part of mobility and has a common occurrence in everyday locomotion[1]. It is a complex task which requires the central nervous system to coordinate body segments reorientation towards a new travel direction while maintaining dynamic body stability[2].

It has been suggested that the complexity of the turning manoeuvre and neural systems involved increases vulnerability to impairment during the turn compared to straight gait[3]. Turning manoeuvres are altered by age[4] and neurological disorders, such as Parkinson's disease[5] or stroke[6]. Turning has been reported as one of the leading activities performed at the time of falling[7] and there is evidence that turning is associated with an increased risk of falling[8]. Therefore, there is a growing part of locomotion research that focuses on turn analysis.

As turning accounts for as much as 45% of steps taken within a day[1], some research has focused on turning performance assessment in a natural living environment[9]. The majority of turning studies have relied on laboratory-based measurements. Most of the instrumented studies involved spatio-temporal, kinematic and/or kinetic parameters to quantify the turn task.

With regard to measurement systems, besides the camera-based motion capture systems, which are widely used in laboratory settings, wearable technologies, especially inertial body sensors, have become an important tool in the field of movement analysis. Their advances, such as portability, ease of use, low cost, and low demand to dedicated space, makes them suitable for utilization in clinical context and opens a promising future for walking turn analysis outside research laboratories. Consequently, it increases attention to walking turn analysis.

This state-of-the-art review aims at providing researchers with an overview of recent instrumented, laboratory-based analysis of 180-degree walking turns and to point out new viable routes for future work. We will examine (1) data acquisition equipment; (2) source signals; (3) performed protocols; (4) turn detection methods; and (5)employed parameters.

A.2 Methods

To obtain a collection of publications within our review scope, we performed a paper search on Scopus, with a set of keywords associated with the topic: (turn AND gait) OR (turn AND walking). With the above keywords, we originally obtained 968 papers. It was further possible to exclude some results after a review of their abstract. In total, we could limit the remaining results to 51 papers published after 2013 (including). We further traversed through referenced sources. In the end 29 papers were kept which addressed 180-degree walking turn analysis.

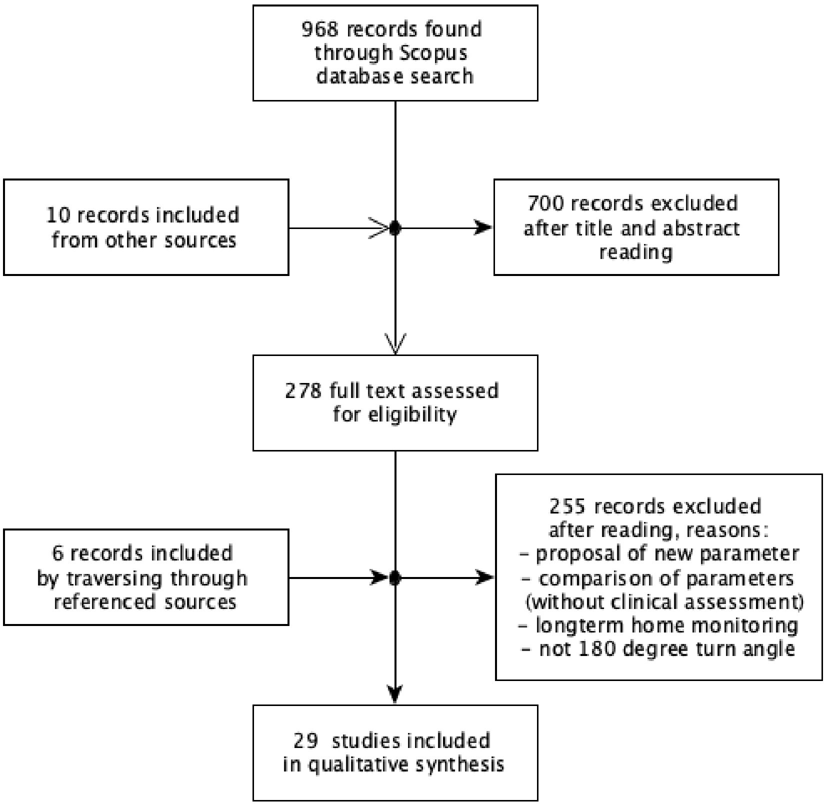
Only papers focusing on turn analysis which brought knowledge about human movement or examined the hypothesized link between turn performance and pathology were considered. Papers which were written without an intention to elucidate or interpret results towards new insight into performing a walking turn, e.g. introducing new parameters or demonstrating novelty algorithms for turn detection, were excluded. Studies dealing with long-term home monitoring were also excluded. Data were extracted from each study, including: turning task, data acquisition devices, processed signals, filters, turn detection method, and turn parameters. The review process is depicted on Fig. A.1.

A.3 Results

A.3.1 Data acquisition devices and source signals

Regarding 180 degree turn studies, 48 % of the studies used camera motion capture systems, 44 % used inertial sensors, and 12 % used force plate measurements of which only one study solely used force plates, one study utilized force plates combined with a video camera, and one study used force plates coupled with a motion camera capture system.

The selection of equipment greatly affects the utilized signals. As the camera motion systems and inertial sensors are widely used in 180 degree turn



Obrázek A.1: Review process.

analysis, the majority of studies (96 %) utilized kinematic signals for further evaluation. Kinetic signals were used for turn parameter computation in 4 % of the studies. Details are provided in Table A.1.

Tabulka A.1: 180 degree turns: protocol, parameters, acquisition systems, detection algorithms.
NR - not reported; turning task notation: distance before turn (m) – turn (°) –distance after turn (m); C - camera motion capture system, IMU - inertial sensors, FP - force plates, * including COM distance, velocity, position, acceleration, and/or trajectory measures (mean, min, max values)

Authors	Turning task	Parameters				HW	Turn detection
		Spatio-temporal	Kinematic	Kinetic	Other		
[10]	TUG	duration	angular rate (max, range), acceleration (range)	-	number of steps	IMU	[11]
[12, 13]	TUG	duration step time before the turn	-	-	number of steps	IMU	[14]
[15]	TUG	duration, phases duration,	lower limbs	-	-	C	[4]
		step length, cadence	joints angles (max)	-	-	C	[4]
[16]	TUG	-	COM derived*	-	-	C	[4]
[17]	TUG	duration, step time	angular rate (max)	-	number of steps	IMU	[14]
[18]	TUG	duration	angular rate (mean, max)	-		C	custom
[19]	TUG	duration	angular rate (mean)	-	number of steps	C	[18]
[20]	TUG	duration	-	-	number of steps	FP, video camera	NR
[21]	TUG	duration, step time	foot clearance (max)	-	number of steps	C	NR
	TUG	variability and symmetry					
[22]	TUG	duration	angular rate (max)	-	-	IMU	custom
[23]	TUG	duration	angular rate (max)	-	-	IMU	custom
[24]	TUG (7 m)	duration	angular rate and acceleration (mean, standard deviation, (max, median, range, RMS)	-	number of steps	IMU	[11]
[25]	ETUG (10 m)	-	angular rate (mean, max), cranio-caudal kinematic turn signature [26]	-	number of steps	IMU	manual
[27]	ETUG (10 m)	duration, step length, step width	inter-segment angle (peak), body segments rotation onset, COM-COP angle (peak)	-	number of steps	C+FP	custom
[28]]	ETUG (10 m)	duration	angular rate (min, max)	-	-	smart phone	[14]
[29]	2 min walk (7 m, 180°)	duration,	angular rate (peak), acceleration (range)	- -	jerkiness	IMU	[30]
[31]	3.5-180°-3.5	step length and width,	-	-	turning strategy	C	NR

Continued on next page

Tabulka A.1 – *Continued from previous page*

Authors	Turning task	Spatio-temporal	Kinematic	Kinetic	Other	HW	Turn detection
[32]	5-180°-5	step time variability turning velocity	COM derived*, segments rotation angle (max)	-	-	C	custom
[33]	5-180°-5	duration, step width	COM derived*	-	-	C	[32]
[34]	9-180°-9	step length, step time	segments rotation angle s(max), turning radius	-	-	C	[35]
[36]	10-180°-10	step length, step width	COM derived*, lower limbs joints angles (max, range)	-	number of steps	C	custom
[37]	ISAW	duration, step time before the turn	-	-	-	IMU	[14]
[38]	i-WALK	duration, step time	angular rate (max)	-	number of steps	IMU	[14]
[39]	SQT	duration	-	COG sway	-	FP	NR
[40, 41]	3 m, semicirc. turn	-	COM derived*	-	-	IMU	a hand switch
[42, 43]	4.65 m, semicirc. turn	turning distance, step length and width, trajectory length, velocity, onset latency	body rotation angle (max)	-	turning strategy	C	[35]

A.3.2 Protocol

According to measurement protocols, the 180-degree turns can be classified into three categories: turning as a part of the Timed Up and Go test (TUG), walking straight followed by a 180 turn, and other protocols.

A functional TUG test, and a modified timed version of the "Get-Up and Go"Test, involves rising from a chair, walking 3m, turning 180°, walking back, and sitting down again. Beside the 3 meters of walking in the TUG, there are also extended variants which usually involves 7 m or 10 m gait. The TUG measurement is simple, requires no special equipment, and is a part of routine clinical examinations. Usually, the time it takes to complete a TUG is assessed. The TUG test is one of the most popular functional assessment tools. Sprint et al. [44] provided a review for instrumented TUG utilization in research.

The second class consists of the subject walking in a straight line followed by a 180 turn and walking back [32, 34, 36, 31, 33]. The length of the straight pathway varies, and it can't be said that a certain length is preferred.

The last class includes various specific protocol with a 180 degree turn, such as the step/quick turn (SQT) test [39], the instrumented stand and walk (ISAW) test [37, 38], i-WALK [38], and a semicircular turn [42, 40, 41]. The SQT test requires taking two steps forward, quickly turning 180° and returning to the starting point. Semicircular turns [40, 41] involve walking 3 m in a straight line, turning in a semicircular curve with a radius of 0.75 m, and then a return on a 3-m straight path. Conradsson et al.[42] used a protocol in which participants walked at their comfortable velocity along a 4.65-meter walking lane. The turning position was marked by two poles and accompanied by an arrow display indicating a semicircular left or right turn or walking straight. The ISAW requires a person to stand still for 30 seconds, initiate gait, walk for 7 m, turn 180 degrees, and walk back to the starting location [45]. The measurement protocol, i-WALK, is an instrumented version of the fixed time-based 2-minute-walk [46]. It involves walking back and forth continuously between two points 25 ft (7.62 m) apart for a period of two minutes.

In summary, walking in a straight line followed by the turn was exploited in 95 % of the studies. Specific tests (e.g. Timed Up & Go test) were adopted in walking turn measurements in 57 % of the studies. The rest of the studies employed other various protocols.

Authors	Signal / Filter	Cut-off frequency [Hz]
[10]	NR	NR
[12, 13]	NR*	NR*
[15]	markers position / low-pass Butterworth	6
[16]	markers position / low-pass Butterworth	6
[17]	NR*	NR*
[18]	NR	NR
[19]	NR	NR
[20]	NR	NR
[21]]	NR	NR
[22]	NR	NR
[23]	AR / high-pass, ACC / low-pass	0.2
[24]	NR	NR
[25]	ACC / high-pass	NR
[27]	NR	NR
[28]	NR	NR
[29]	AR / low-pass Butterworth	1.5
[31]	markers position / low-pass Butterworth	5
[32]	NR	NR
[33]	NR	NR
[34]	markers position / low-pass Butterworth	7
[36]	markers position derivative / low-pass Butterworth	4
[37]	NR*	NR*
[38]	NR*	NR*
[39]	NR	NR
[40, 41]	NR	NR
[42, 43]	markers position / low-pass Butterworth	7

Tabulka A.2: Raw signal filtering in 180 degree turns processing.
NR - not reported, * uses commercially available data acquisition system, processing details are proprietary and unpublished

A.3.3 Filtering

The preprocessing main objective is the preparation of the signal for the following processing step. This first block of operations aims to extract only relevant data to the analysis from the measured (raw) signals avoiding contamination due to artifacts and noise. Pre-processing is usually a two-step procedure: the definition of the filter and the turn segment detection.

A measurement noise is an undesirable portion of any kinematic waveform.

It can be caused by soft tissue artefact, improper attachment of sensors/markers and electrical interference[47]. The objective of any filtering technique is not only to attenuate noise but also to leave the true signal unaffected[48].

In Table A.2 the filters employed in turn analysis are shown, most of the studies did not report filter and/or filter parameters (XX %). All studies reporting filtering of camera system data used low-pass Butterworth filters. Filters reported regarding IMU signals vary (low-pass and high-pass filter are used).

A.3.4 Turn detection techniques

The detection of the beginning and the end of the walking turn is a basic step needed to calculate credible turn parameters. Thigpen and coworkers [4], using video-taping, defined the turn as the beginning and end of the 180-degree reversal of direction at the turn line on the floor while walking. This method was later adopted by researchers using motion camera systems[15, 16, 32]. Another technique to identify the turn onset employs foot markers (e.g. heel, toe). The first turning step is delimited as the step exceeding 200 % of the standard deviation in the medio-lateral displacement of walking straight[35, 34, 42].

Salarian et al.[14] presented a method using one IMU to obtain turn signals. This method was based on a signal from a yaw gyroscope on the sternum. Turning components appear as positive or negative ramps of an angle from the trunk. Recently this approach was adapted to camera motion systems[18]. Weiss et al.[11, 10] determined turns from the lower back yaw signal as the point in which the signal crossed 10 % of the maximum yaw amplitude of the turn. El-Gohary et al.[30] used IMU placed on the lower back and defined the start and end of the turn as an angular rate exceeding a threshold of 5 deg/s.

Lastly, some authors used custom detection techniques to obtain the onset and the end of the 180 degrees walking turn. For instance, Shin et al.[40, 41] used a hand switch to partition turn movement from walking straight. Yang et al.[27] defined the turn onset and end of the turn as the earliest onset and the latest end of the body segments rotation. Uem et al.[22] determined the start and end of turning using threshold detection in squared angular velocity around the vertical axis. Vervoort et al. [24] detected a turn via Daubechies 5 mother wavelet. Another custom method based on a gyroscope signal detected the start as a dramatic increase of the angle in the yaw direction and the end when the signal became stable again [23]. The exact slope threshold is not presented in the study. Spildooren et al.[32] compared the orientation of body markers to external markers which defined the turning place. Serrao et al.[36] started the turn by an acoustic cue and identified the end when the body rotation angle fell within a boundary of 180 degree ± 300 % of a standard deviation of the walking straight body rotation angle.

A.3.5 Parameters

In total, 66 different parameters were assessed in the reviewed literature. These parameters were categorized as spatio-temporal (27 %), kinematic (42 %), of which 15 % were acceleration-derived and 38 % were orientation-derived, kinetic (18 %) and other (6 %).

Out of 12 studies utilizing inertial signals (i.e. IMU systems or smartphone), 10 studies employed turn duration, 6 studies number of steps, and 9 studies descriptive statistics of the signals (e.g. max, mean). Minority parameters are: turn step time (2 studies), step time before the turn (2 studies), center of mass (COM) derived parameters (2 studies), jerkiness of the turn (1 study). Turn duration is determined as the duration from the beginning until the end of the turn [10, 22, 23, 24, 29, 28]. Steps and related parameters (e.g. number of steps) are derived from the acceleration in the vertical axis of the sensor located on the lower back [10, 24] or on the feet [25]. Center of mass derived parameters are estimated from a single sensor located near the body COM [40, 41]. Six studies used commercially available data acquisition IMU based systems [12, 13, 17, 37, 38, 29]. Most of them did not report in detail the procedure of parameter estimation [12, 13, 17, 37, 38].

Only one motion capture system-based study (out of 12) used no spatio-temporal parameter for turn assessment (they used only COM derived parameter). Other studies employed turn duration (6 studies), step length (6 studies) and/or width (5 studies), step time-based parameters (3 studies), number of steps (5 studies), cadence during turning (1 study), turning distance (1 study), turning trajectory length (1 study). Also, COM derived parameters were calculated (5 studies). Descriptive statistics of body segments or joint angles (6 studies), and angular rate (2 studies) were also used.

The computation of spatio-temporal parameters during turning initially proposed by Huxham et al. [49] was employed by [27, 31, 33, 34, 36, 42, 43]. Other studies did not report their approach to calculation of spatio-temporal parameters [15, 16, 18, 19, 21]. COM was estimated using centroid of a 12-segment [16] and 15-segment [33, 36, 32, 27] model.

Three studies used force plates. Only one of them used a force plate as a sole acquisition device and determined turn duration and COG trajectory [39] . Second study used force place along with a video-camera [20]. They calculated turn duration and number of steps but did not report details of parameters estimation. Yang et al. [27] employed a force plate together with a 3D camera motion capture system. From a force plate they used to record the COP during turning (the rest of the parameters were determined from a camera system).

A.3.6 Research areas

Studies focusing on the walking turns of patients with Parkinson disease (PD) are an important class of walking turn analysis. Yang et al.[27] investigated the rotation of segments and gait instability during turns in people with PD. For this purpose, they used the following parameters: turning time, turning steps, COM-COP inclination angle, and body segments' angles. Lebel et al.[25] analysed the cranio-caudal rotational sequence of PD. Four spatio-temporal parameters were used to examine the effect of clock-turn strategy in PD[21]. Also, Uem et al.[22] dealt with turn analysis of PD patients via turn duration and maximal angular rate. Bhatt et al.[31] investigated turning strategy (step, spin) relating to freezing of gait (FOG) in PD. Spildooren et al. [32] examined the relationship between impaired head-pelvis rotation during turning and FOG in PD. Bengewoord et al.[33] differentiated freezers and non-freezers via spatio-temporal parameters and COM movement. Bertoli et al.[29] compared turn parameters derived from inertial measurement units across PD subjects with and without FOG. To analyse the relationship between turning performance and falls in PD Cheng et al. [39] used turn duration and COM velocity. Horak et al.[37] employed spatio-temporal parameters to analyse balance and gait in PD. Conradsson et al.[42] studied the effect of medication in PD to planned and unplanned turns using turning strategy, spatio-temporal and kinematic parameters.

Age related research is another class of walking turn investigation including balance assessment. Weiss et al.[10] employed kinematic turn parameters to identify subclinical gait impairments in a community dwelling older adults. To distinguish performance differences across age Vervoort et al.[38] extracted turn duration and amplitude characteristics of angular rate and acceleration among 27 TUG variables. Forse et al.[34] evaluated the effect of walking velocity on axial coordination during turns in healthy older adults. COM acceleration and energy expenditure were analysed in semicircular turns in elderly women[40, 41]. The relationship between cognitive domains, gait and balance was analysed by Pal et al.[33] via spatio-temporal and angular rate-derived parameters. The additional value of turn assessment for the association between clinical walking tests and self-reported measures of walking and balance was evaluated by Adusumilli et al.[17]. They employed body worn sensors and extracted four kinematic parameters from measured signals. The effect of walking speed on medio-lateral stability during turning was explored in older adults[43].

Beside PD and age, a number of different diseases was studied via turn analysis. O'Keefe et al.[12, 13] utilized turn duration, step time before the turn, and the number of steps in the turn to characterize mobility deficits in fragile X-associated tremor/ataxia syndrome.

Bonnyaud et al.[15] involved the TUG in the analysis of movement in stroke patients during two conditions: spontaneous and standardized condition. The turn sub-task performance was represented by the time it took to turn, the percentage of single support swing phases, and the kinematic parameters of the joints. Using the same protocol, they compared COM trajectory to reference COM trajectory by Hausdorff distance and dynamic time warping[16].

Serrao et al.[36] analysed turn strategies of cerebellar ataxia patients. To evaluate body behaviour during turning, they calculated body rotation and COM velocity at the heel strike for each step, step width and length, and joint angles.

Using a camera system Ansai et al.[19] compared the performance of the TUG and all its subtasks (sit-to-stand transition, walking forward, 180 degree turn, walking back, turn-to-sit transition) of prospective fallers and non-fallers with cognitive impairment and Alzheimer's disease.

Bovonsunthonchai et al.[20] investigated the effect of the spinal tap test on the motor abilities of patients with idiopathic normal pressure hydrocephalus. The study involved three tasks: sit-to-stand, walking, and 180 degree turning. Objective measures computed for the turning task were turning time and the number of steps.

A summary of protocols, parameters and measurement systems utilized in 180 degree turn analysis is provided in Table A.1.

A.4 Discussion

This article provided an overview of methodologies used in recent research for the walking turn. We reviewed protocol, signals, parameters, detection methods, and data acquisition systems employed in walking turn assessment.

A.4.1 Protocol

A number of different protocols has been used for walking turn assessment recently, however, several questions arise. As can be seen from the review, most of the walking turns are preceded by straight walking for less than 5 meters. Turning is influenced by gait velocity[35]. Thus, it can be assumed that performing a turn before the end of gait initiation, the transient period between quiet standing and a steady state of walking, affects turning parameters. Opinions about the number of steps needed to reach a steady gait are not uniform and vary according subjects' groups types[50, 51]. It follows that the distance of straight walking before the turn should be taken into account when planning protocol, and also when interpreting results. The number of steps after the turn also varies across the studies. The effect of anticipation of gait termination and the distance behind the turn has not been analysed yet. The lack of consensus regarding turn protocol may limit cross-research and intergroup comparisons.

Most of the protocol consists of a single turn, e.g., TUG. However, some protocol, e.g, i-WALK, comprised of multiple turns and parameter values are averaged from all performed turns[45]. Regarding cross-research comparability, in multiple turn protocol the training effect on turn kinematic should be taken into account.

A.4.2 Signals

A turn-related reliability analysis of different subject groups was performed for peak angular rate[14, 52, 53], mean angular rate[53], duration[14, 52], midpoint turn time[52], number of steps[14, 52], and timing of steps[14]. Based on evidence, turn derived parameters are less reliable than gait parameters for straight locomotion[14, 52]. However, the reliability of turn movement itself has not been explored yet. Moreover, previous research hasn't compared reliability for different subject groups. Similar to gait, the analysis of turn variability may increase new knowledge relating to specific types of pathology.

It would be beneficial to researchers if a range of "normal" turn kinematics were defined for continuous turn signals. In this way, new subjects could be classified as belonging or not belonging to the group[54].

A.4.3 Filtering

It is common practice to low-pass filter the kinematic data in order to reduce the effects of measurement noise. It is crucial to choose an appropriate filtering procedure and decide what cut-off frequency should be chosen in this procedure. If a high cut-off frequency is used, very little noise will be removed. On the other hand, a low cut-off frequency will introduce artifacts into the trajectory [55]. Based on this review, the reporting of filters used in the study and their parameters is insufficient.

A.4.4 Parameters

If we focus on the parameters utilized in walking turn assessment, the most frequently used are spatio-temporal parameters adopted from gait analysis (e.g. stride length, stride width, and duration of gait cycles phases). This is probably because the calculation is simple, interpretation intuitive and there is evidence that spatio-temporal parameters are related to stability and increased fall risk for gait and turning which is an important topic in movement analysis. In addition, it might be related to data acquisition systems currently used. The most widespread system in turn analysis is the camera motion capture system and the authors employ algorithms proposed by Huxham[49] to compute temporal variables for non-linear walking, e.g. turns, based on camera system data. With an increasing number of researchers utilizing inertial sensors, acceleration and angular rate derived parameters have also been used. Unfortunately, only basic parameters, e.g. maximum and minimum, are usually computed as a standard indicator.

Most data acquisition systems provide continuous signals in three dimensions over the whole turn and these signals can be useful data sources. Thus, new more complex parameters should be utilized to improve quantitative turn assessment [56]. New parameters might embody the shape of the turn curve and should be provided together with its movement related interpretation.

A.4.5 Data acquisition

Although instrumented movement analysis has been used for several decades, it has been performed mainly in a laboratory environment. A growing demand for the utilization of movement analysis in clinical and home settings together with rapid progress with wearable sensors convey their usage to the field of walking turn analysis. Prevalent acquisition devices are camera motion systems and inertial measurement units. Nevertheless, new approaches to record and process turn data arise, including smart phones[28], tablets[57] and depth cameras[58].

The quality and validity of movement analysis are dependent on measuring instruments used[59]. However, there is no defined consensus on what parameters should be computed when using different data acquisition systems, e.g. camera system, inertial units. Movement parameters are influenced by data processing techniques[60]. Comparisons should be performed across systems to determine which system is appropriate with respect to specific parameters. An interpretation of results should be careful to identify how much parameters values are driven by movement and how much is due to the function of data acquisition and processing techniques.

A.4.6 Turn detection

Unbiased signal processing requires an automatic detection of the turn and consequent parameters of evaluation. A large amount of research based on an automatically detected turn comes from Salarian et al.[14]. Another area of growing research in the field is based on Greene et al. work[61]. Both algorithms utilized inertial sensors as data acquisition hardware and processed trunk angular rate data to detect the TUG turn. Some researchers used custom designed methods, manual segmentation by examining a graphical representation of specific marker displacements, adjusted straight walking length (starting point) so that the turn started by stepping on force plate, and well as many others approaches (refer to Table A.1). Some studies did not report an approach for detection of the parts of turn at all. As a proper detection of the onset and offset of the turn is crucial for turn assessment and comparison of results, a collation of a detection method should be provided. Standardized definitions in relation to the walking turn and its sub-phases could improve consistency in reporting.

Finally, instrumented turn analysis is becoming widely adopted in human movement research. It has the capability of pointing out functional and/or cognitive decline[62] as well as revealing higher risk of falls[8]. Thus, it has the potential to become a part of clinical assessment. To enable turn assessment to be adopted in clinical practice, we recommend using portable systems with low requirements on measurement space. Regarding protocols, utilization of the TUG seems to be a feasible solution. It is recommended by the American and British Geriatrics Societies as a screening tool for identifying older people at a higher risk of falling and if instrumented it can provide additional and reliable gait data[52]. Based on the above, we recommend using inertial measurement systems along with the Timed Up & Go test as a viable route to the adoption of turn analysis in a clinical context.

A.5 Conclusion

The aim of this review paper was to provide an overview of turn parameters together with data acquisition equipment to pose data sources available to quantify kinematics and dynamics of the turn manoeuvre. A large number of recent articles were found on 180-degree walking turn analysis. These papers included original articles employing walking turn analysis; a big portion of the studied articles described using a camera system or wearable sensors; and a small number of studies presented analysis via force plates. Finally, the methodology of turn analysis' advantages and limitations, and proposals for further research directions were discussed.

A.6 References

[1] B. C. Glaister, G. C. Bernatz, G. K. Klute, and M. S. Orendurff, "Video task analysis of turning during activities of daily living," *Gait & Posture*, vol. 25, pp. 289–294, 2018/07/08 2007.

[2] A. E. Patla, A. Adkin, and T. Ballard, "Online steering: coordination and control of body center of mass, head and body reorientation," *Experimental Brain Research*, vol. 129, pp. 629–634, Dec 1999.

[3] T. Herman, N. Giladi, and J. M. Hausdorff, "Properties of the 'timed up and go' test: more than meets the eye," *Gerontology*, vol. 57, pp. 203–210, 04 2011.

[4] M. T. Thigpen, K. E. Light, G. L. Creel, and S. M. Flynn, "Turning difficulty characteristics of adults aged 65 years or older," *Physical Therapy*, vol. 80, no. 12, pp. 1174–1187, 2000.

[5] P. Crenna, I. Carpinella, M. Rabuffetti, E. Calabrese, P. Mazzoleni, R. Nemni, and M. Ferrarin, "The association between impaired turning and normal straight walking in parkinson's disease," *Gait & Posture*, vol. 26, pp. 172–178, 2018/07/08 2007.

[6] K. L. Hollands, P. van Vliet, D. Zietz, A. Wing, C. Wright, and M. A. Hollands, "Stroke-related differences in axial body segment coordination during preplanned and reactive changes in walking direction," *Experimental Brain Research*, vol. 202, pp. 591–604, May 2010.

[7] S. N. Robinovitch, F. Feldman, Y. Yang, R. Schonnop, P. M. Lueng, T. Sarraf, J. Sims-Gould, and M. Loughin, "Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study," *Lancet (London, England)*, vol. 381, pp. 47–54, 01 2013.

[8] R. L. Wright, D. M. Peters, P. D. Robinson, A. J. Sitch, T. N. Watt, and M. A. Hollands, "Differences in axial segment reorientation during standing turns predict multiple falls in older adults," *Gait & Posture*, vol. 36, no. 3, pp. 541 – 545, 2012.

[9] J. M. Leach, S. Mellone, P. Palumbo, S. Bandinelli, and L. Chiari, "Natural turn measures predict recurrent falls in community-dwelling older adults: a longitudinal cohort study," *Scientific Reports*, vol. 8, no. 1, p. 4316, 2018.

[10] A. Weiss, A. Mirelman, A. Buchman, D. Bennett, and J. Hausdorff, "Using a body-fixed sensor to identify subclinical gait difficulties in older adults with iadl disability: Maximizing the output of the timed up and go," *PLoS ONE*, vol. 8, no. 7, 2013. cited By 24.

[11] A. Weiss, T. Herman, M. Plotnik, M. Brozgol, N. Giladi, and J. M. Hausdorff, "An instrumented timed up and go: the added value of an accelerometer for identifying fall risk in idiopathic fallers," *Physiological Measurement*, vol. 32, no. 12, p. 2003, 2011.

[12] J. O'Keefe, E. Robertson-Dick, D. Hall, and E. Berry-Kravis, "Gait and functional mobility deficits in fragile x-associated tremor/ataxia syndrome," *Cerebellum*, vol. 15, no. 4, pp. 475–482, 2016. cited By 3.

[13] J. O'Keefe, E. Robertson, B. Ouyang, D. Carns, A. McAsey, Y. Liu, M. Swanson, B. Bernard, E. Berry-Kravis, and D. Hall, "Cognitive function impacts gait, functional mobility and falls in fragile x-associated tremor/ataxia syndrome," *Gait and Posture*, vol. 66, pp. 288–293, 2018. cited By 0.

[14] A. Salarian, F. Horak, C. Zampieri, P. Carlson-Kuhta, J. Nutt, and K. Aminian, "Itug, a sensitive and reliable measure of mobility," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, pp. 303–310, 6 2010.

[15] C. Bonnyaud, D. Pradon, N. Vuillerme, D. Bensmail, and N. Roche, "Spatiotemporal and kinematic parameters relating to oriented gait

and turn performance in patients with chronic stroke," *PLoS ONE*, vol. 10, no. 6, 2015. cited By 6.

[16] C. Bonnyaud, N. Roche, A. Van Hamme, D. Bensmail, and D. Pradon, "Locomotor trajectories of stroke patients during oriented gait and turning," *PLOS ONE*, vol. 11, pp. 1–14, 02 2016.

[17] G. Adusumilli, S. Lancia, V. A. Levasseur, V. Amblee, M. Orchard, J. M. Wagner, and R. T. Naismith, "Turning is an important marker of balance confidence and walking limitation in persons with multiple sclerosis," *PLOS ONE*, vol. 13, pp. 1–10, 06 2018.

[18] J. H. Ansai, A. C. S. Farche, P. G. Rossi, L. P. de Andrade, T. H. Nakagawa, and A. C. d. M. Takahashi, "Performance of different timed up and go subtasks in frailty syndrome," *Journal of Geriatric Physical Therapy*, vol. Publish Ahead of Print, 9000.

[19] J. Ansai, L. de Andrade, T. Nakagawa, and J. Rebelatto, "Performances on the timed up and go test and subtasks between fallers and nonfallers in older adults with cognitive impairment [performances no teste timed up and go e subtarefas em idosos com comprometimento cognitivo, caidores e não caidores]," *Arquivos de Neuro-Psiquiatria*, vol. 76, no. 6, pp. 381–386, 2018. cited By 0.

[20] S. Bovonsunthonchai, T. Witthiwej, C. Ngamsombat, S. Sathornsumetee, R. Vachalathiti, W. Muangpaisan, P. Hengsomboon, S. Thong-On, S. Jankhum, and P. Yangyoo, "Effect of spinal tap test on the performance of sit-to-stand, walking, and turning in patients with idiopathic normal pressure hydrocephalus," *Nagoya Journal of Medical Science*, vol. 80, no. 1, pp. 53–60, 2018. cited By 0.

[21] W.-C. Yang, W.-L. Hsu, R.-M. Wu, and K.-H. Lin, "Immediate effects of clock-turn strategy on the pattern and performance of narrow turning in persons with parkinson disease," *Journal of Neurologic Physical Therapy*, vol. 40, no. 4, pp. 249–256, 2016. cited By 1.

[22] J. Van Uem, S. Walgaard, E. Ainsworth, S. Hasmann, T. Heger, S. Nussbaum, M. Hobert, E. Micó-amigo, R. Van Lummel, D. Berg, and W. Maetzler, "Quantitative timed-up-and-go parameters in relation to cognitive parameters and health- related quality of life in mild-to-moderate parkinson's disease," *PLoS ONE*, vol. 11, no. 4, 2016. cited By 7.

[23] N. A. Zakaria, Y. Kuwae, T. Tamura, K. Minato, and S. Kanaya, "Quantitative analysis of fall risk using TUG test," *Computer Methods in Biomechanics and Biomedical Engineering*, 2015.

[24] D. Vervoort, N. Vuillerme, N. Kosse, T. Hortobágyi, and C. Lamoth, "Multivariate analyses and classification of inertial sensor data to identify aging effects on the timed-up-and-go test," *PLoS ONE*, vol. 11, no. 6, 2016. cited By 2.

[25] K. Lebel, C. Duval, H. Nguyen, R. Plamondon, and P. Boissy, "Cranio-caudal kinematic turn signature assessed with inertial systems as a marker of mobility deficits in parkinson's disease," *Frontiers in Neurology*, vol. 9, no. JAN, 2018. cited By 0.

[26] K. Lebel, H. Nguyen, C. Duval, R. Plamondon, and P. Boissy, "Capturing the cranio-caudal signature of a turn with inertial measurement systems: Methods, parameters robustness and reliability," *Frontiers in bioengineering and biotechnology*, vol. 5, pp. 51; 51–51, 08 2017.

[27] W.-C. Yang, W.-L. Hsu, R.-M. Wu, T.-W. Lu, and K.-H. Lin, "Motion analysis of axial rotation and gait stability during turning in people with parkinson's disease," *Gait & Posture*, vol. 44, pp. 83 – 88, 2016.

[28] A. Galán-Mercant and A. I. Cuesta-Vargas, "Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks," *BMC Research Notes*, 2014.

[29] M. Bertoli, A. Cereatti, U. Della Croce, and M. Mancini, "An objective assessment to investigate the impact of turning angle on freezing of gait in parkinson's disease," vol. 2018-January, pp. 1–4, 2018. cited By 0.

[30] M. El-Gohary, S. Pearson, J. McNames, M. Mancini, F. Horak, S. Mellone, and L. Chiari, "Continuous monitoring of turning in patients with movement disability," *Sensors*, vol. 14, no. 1, pp. 356–369, 2014.

[31] H. Bhatt, F. Pieruccini-Faria, and Q. Almeida, "Dynamics of turning sharpness influences freezing of gait in parkinson's disease," *Parkinsonism and Related Disorders*, vol. 19, no. 2, pp. 181–185, 2013. cited By 19.

[32] J. Spildooren, S. Vercruysse, E. Heremans, B. Galna, J. Vandenbossche, K. Desloovere, W. Vandenberghe, and A. Nieuwboer, "Head-pelvis

coupling is increased during turning in patients with parkinson's disease and freezing of gait," *Movement Disorders*, vol. 28, no. 5, pp. 619–625, 2013. cited By 12.

[33] A. Bengevoord, G. Vervoort, J. Spildooren, E. Heremans, W. Vandenberghe, B. Bloem, and A. Nieuwboer, "Center of mass trajectories during turning in patients with parkinson's disease with and without freezing of gait," *Gait and Posture*, vol. 43, pp. 54–59, 2016. cited By 9.

[34] C. Forsell, D. Conradsson, C. Paquette, and E. Franzén, "Reducing gait speed affects axial coordination of walking turns," *Gait and Posture*, vol. 54, pp. 71–75, 2017. cited By 0.

[35] S. B. Akram, J. S. Frank, and S. Chenouri, "Turning behavior in healthy older adults: Is there a preference for step versus spin turns?," *Gait & Posture*, vol. 31, pp. 23–26, 2018/07/08 2010.

[36] M. Serrao, S. Mari, C. Conte, A. Ranavolo, C. Casali, F. Draicchio, R. Di Fabio, M. Bartolo, S. Monamì, L. Padua, and F. Pierelli, "Strategies adopted by cerebellar ataxia patients to perform u-turns," *Cerebellum*, vol. 12, no. 4, pp. 460–468, 2013. cited By 10.

[37] F. B. Horak, M. Mancini, P. Carlson-Kuhta, J. G. Nutt, and A. Salarian, "Balance and gait represent independent domains of mobility in parkinson disease," *Physical Therapy*, vol. 96, pp. 1364–1371, 09 2016.

[38] G. Pal, J. O'Keefe, E. Robertson-Dick, B. Bernard, S. Anderson, and D. Hall, "Global cognitive function and processing speed are associated with gait and balance dysfunction in parkinson's disease," *Journal of NeuroEngineering and Rehabilitation*, vol. 13, no. 1, pp. 1–8, 2016. cited By 1.

[39] F.-Y. Cheng, Y.-R. Yang, C.-J. Wang, Y.-R. Wu, S.-J. Cheng, H.-C. Wang, and R.-Y. Wang, "Factors influencing turning and its relationship with falls in individuals with parkinson's disease," *PLoS ONE*, vol. 9, no. 4, 2014. cited By 10.

[40] S.-S. Shin, D.-H. An, and W.-G. Yoo, "Effects of balance recovery after square and semicircular turns on gait velocity and center of mass acceleration in older adults with differing visual acuity," *European Geriatric Medicine*, vol. 6, no. 2, pp. 103–108, 2015. cited By 4.

[41] S.-S. Shin, D.-H. An, and W.-G. Yoo, "Effects of balance control through trunk movement during square and semicircular turns on gait velocity, center of mass acceleration, and energy expenditure in older adults," *PM and R*, vol. 8, no. 10, pp. 953–961, 2016. cited By 2.

[42] D. Conradsson, C. Paquette, J. Lökk, and E. Franzén, "Pre- and unplanned walking turns in parkinson's disease – effects of dopaminergic medication," *Neuroscience*, vol. 341, pp. 18 – 26, 2017.

[43] D. Conradsson, C. Paquette, and E. Franzén, "Medio-lateral stability during walking turns in older adults," *PLoS ONE*, vol. 13, no. 6, 2018. cited By 1.

[44] G. Sprint, D. Cook, and D. L Weeks, "Towards automating clinical assessments: A survey of the timed up and go (tug)," *IEEE reviews in biomedical engineering*, vol. 8, 01 2015.

[45] M. Mancini, L. King, A. Salarian, L. Holmstrom, J. McNames, and F. B. Horak, "Mobility lab to assess balance and gait with synchronized body-worn sensors," *Journal of bioengineering & biomedical science*, vol. Suppl 1, pp. 007–, 12 2011.

[46] R. J. Butland, J. Pang, E. R. Gross, A. A. Woodcock, and D. M. Geddes, "Two-, six-, and 12-minute walking tests in respiratory disease," *British medical journal (Clinical research ed.)*, vol. 284, pp. 1607–1608, 05 1982.

[47] D. A. Winter, H. Sidwall, and D. A. Hobson, "Measurement and reduction of noise in kinematics of locomotion," *Journal of Biomechanics*, vol. 7, no. 2, pp. 157 – 159, 1974.

[48] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. New York: Wiley, 2nd ed. ed., 1990.

[49] F. Huxham, J. Gong, R. Baker, M. Morris, and R. Iansek, "Defining spatial parameters for non-linear walking," *Gait & Posture*, vol. 23, pp. 159–163, 2018/07/08 2006.

[50] A. K. E., V. Beatrix, and S. P. E., "What changes in infant walking and why," *Child Development*, vol. 74, no. 2, pp. 475–497, 2003.

[51] U. Lindemann, B. Najafi, W. Zijlstra, K. Hauer, R. Muche, C. Becker, and K. Aminian, "Distance to achieve steady state walking speed in

frail elderly persons," *Gait & Posture*, vol. 27, pp. 91–96, 2018/07/08 2008.

[52] E. Smith, L. Walsh, J. Doyle, B. Greene, and C. Blake, "The reliability of the quantitative timed up and go test (qtug) measured over five consecutive days under single and dual-task conditions in community dwelling older adults," *Gait & Posture*, vol. 43, pp. 239–244, 2018/07/08 2016.

[53] M. A. Newman, M. A. Hirsch, R. D. Peindl, N. A. Habet, T. J. Tsai, M. S. Runyon, T. Huynh, and N. Zheng, "Reliability of the subcomponents of the instrumented timed up and go test in ambulatory children with traumatic brain injury and typically developed controls," *Gait & Posture*, vol. 63, pp. 248–253, jun 2018.

[54] M. W. Lenhoff, T. J. Santner, J. C. Otis, M. G. E. Peterson, B. J. Williams, and S. I. Backus, "Bootstrap prediction and confidence bands: a superior statistical method for analysis of gait data," *Gait & Posture*, vol. 9, pp. 10–17, 2018/07/08 1999.

[55] S. Schreven, P. J. Beek, and J. B. Smeets, "Optimising filtering parameters for a 3d motion analysis system," *Journal of Electromyography and Kinesiology*, vol. 25, no. 5, pp. 808 – 814, 2015.

[56] S. Viteckova, R. Krupicka, V. Cejka, P. Kutilek, Z. Szabo, E. Růžička, and P. Dusek, "Waveform skewness: Parameter for timed up & go turn assessment," *Biomedical Signal Processing and Control*, vol. 52, pp. 347 – 352, 2019.

[57] M. M. Koop, S. J. Ozinga, A. B. Rosenfeldt, and J. L. Alberts, "Quantifying turning behavior and gait in parkinson's disease using mobile technology," *IBRO Reports*, vol. 5, pp. 10 – 16, 2018.

[58] A. Dubois, T. Bihl, and J.-P. Bresciani, "Automating the timed up and go test using a depth camera," *Sensors (Switzerland)*, vol. 18, no. 1, 2018. cited By 1.

[59] S. R. Simon, "Quantification of human motion: gait analysis—benefits and limitations to its application to clinical problems," *Journal of Biomechanics*, vol. 37, no. 12, pp. 1869 – 1880, 2004.

[60] C. K. Rhea, A. W. Kiefer, W. G. Wright, L. D. Raisbeck, and F. J. Haran, "Interpretation of postural control may change due to data pro-

cessing techniques," *Gait & Posture*, vol. 41, pp. 731–735, 2018/07/08 2015.

[61] B. R. Greene, A. O'Donovan, R. Romero-Ortuno, L. Cogan, C. N. Scanaill, and R. A. Kenny, "Quantitative falls risk assessment using the timed up and go test," *IEEE Transactions on Biomedical Engineering*, vol. 57, pp. 2918–2926, Dec 2010.

[62] A. Mirelman, A. Weiss, A. S. Buchman, D. A. Bennett, N. Giladi, and J. M. Hausdorff, "Association between performance on timed up and go subtasks and mild cognitive impairment: further insights into the links between cognitive and motor function," *Journal of the American Geriatrics Society*, vol. 62, pp. 673–678, 04 2014.

Příloha B

Cíl 1: Vlastní publikace

The Timed Up & Go test sit-to-stand transition: which signals measured by inertial sensors are viable route for continuous analysis?

Introduction

The Timed Up and Go (TUG) test is a well-known clinical test for assessment of mobility and fall risk. It involves standing from a chair, walking straight, turning, walking back to the chair, and sitting back in the chair. Several studies have augmented the utility of the TUG by using instrumentation [1,2], e.g. with inertial measurement units (IMU). The main advantage of IMUs is that they are wearable and cheaper compared to camera systems; therefore, their usage is increasing.

It has been shown that IMU which use an accelerometer and gyroscope are capable of analysing quantitative parameters of the sit-to-stand transition (StS)[3]. Usually, acceleration [1,2,4] and angular velocity [1,2] serve as source signals for the computation of discrete StS parameters: minimal[5], maximal[2,5], median[4] or mean[1,5] value, and the standard deviation [4].

In comparison to the analyses of above mentioned discrete parameters, an analysis of the continuous curve is more informative [6]. For optimal interpretation of the analysis of continuous curves, the signal pattern must be considered. The pattern of corresponding signals should be specific for different subject groups, e.g. patients with a particular diagnosis[7]. Besides, when the pattern is known, the inter-subject variability along this pattern can be informative and useful [8]. To date, however, it is not clear which signal provided by the IMU is most suitable for TUG continuous analysis.

The main aim of the paper is to identify which signals obtained by the IMU are suitable for continuous transition analysis in Parkinson disease patients and older healthy adults. To achieve this, we addressed the following partial-goals: (1) to ascertain signal patterns shared within the subject group, and (2) to evaluate the variability of transition signals within a subject group.

Methods

Participants and Data Acquisition

In the analysis we included 29 older adult volunteers (24 males, 5 females), mean age 62.9 (SD 8.4) years free from any neurological or psychiatric disorder as the control groups (CG), and 31 de-novo Parkinson disease (PD) patients (20 males, 11 females), mean age 60.5 (SD 12.6) years (details provided in Supplementum 1). The study was approved by the Ethics Committee of the

General University Hospital in Prague, Czech Republic. A written, informed consent was obtained prior to data collection.

All subjects performed an instrumented extended 10m-TUG wearing a gyro-accelerometer (MTx units, Xsens Technologies B.V., Netherlands) placed on the subject's chest, 2 cm below the sternal notch (sample frequency of 100 Hz). The three-dimensional kinematic signals, i.e. angular velocity about the roll-axis (ω_{roll}), pitch-axis (ω_{pitch}), and yaw-axis (ω_{yaw}); and vertical (a_V), medio-lateral (a_{ML}), and antero-posterior (a_{AP}) acceleration, were analysed.

Preprocessing

The StS transition was detected as the movement with a ω_{pitch} higher than 10 deg/s [9]. As a negative angular velocity indicates a clockwise rotation, the beginning of the StS was detected from the ω_{pitch} as a value less than -10 deg/s. The end of StS was identified as a value lower than 10 deg/s. All data analysis was carried out in Matlab 2015 (MathWorks Inc., Natick, USA).

Signals analysis

Signal pattern

In the analysis of continuous physiological signals including movement analysis, intra-class correlation (ICC) has been suggested [10] and adopted for quantification of the curves similarity [7,11]. Due to natural inter-individual variability, different scaling of signals can be observed across each subjects' group. Therefore, we employed the two-way random effects, consistency, single measurements ICC[12]. The ICC was computed for each point along the entire StS curve[7].

Inter-subjects' variability

The variability among subjects can be studied via prediction bands [8,13]. Based on recent studies [11,14,15], the bootstrap method is a suitable application for movement kinematic data. 95% prediction bands via bootstrap were computed with 1000 bootstrap samples (details in Lenhoff et al. [8]). The true coverage probability was determined by cross-validation [8]. As the absolute value of prediction bands' width is not comparable across different signals, the ratio of prediction bands' width to signals mean is stated.

Results

Signal pattern

The ω_{pitch} exhibited the best signal match across subjects in both groups ($0.50<ICC<0.75$). The a_{AP} also showed moderate inter-subjects signal match in the CG ($0.50<ICC<0.75$). Other signals demonstrated a poor signal pattern ($ICC<0.50$), Table 1.

Inter-subjects' variability

The prediction bands in both groups are shown on Fig. 1. The results of the cross-validation calculations are shown in Table 1. In the CG, the estimated true achieved coverage ranged from 86 % to 93 % for acceleration curves and from 72 % to 86 % for angular velocities. In PD the results for acceleration and angular velocity were slightly lower than in the CG (ranged from 80 % to 87 %, 74 % to 77% resp.). The ratio of prediction bands' width to signals mean is shown in Fig. 2.

Discussion

Slightly stronger intra-class correlations in the CG than PD were observed in all statistically significant results. This is consistent with a previous study of walking turn signals in PD and the CG [7]. An analysis of the common signal pattern indicated that ω_{pitch} had the most characteristic patterns for StS, which corresponds with intuitive processing of ω_{pitch} in previous studies [2,9]. As the ω_{roll} in PD was not statistically significant and the signal pattern in the CG was negligible but statistically significant, we do not expect a distinctly stronger pattern in PD then in the CG. The ω_{yaw} did not have a significant result in the CG. Therefore, further analysis should be considered. There are two possible explanation for group means close to zero. First, the subjects' signals are close to zero. Second, the subjects' signals have an opposite signum. The ω_{yaw}, ω_{roll}, and a_{ML} signals approach zero and yield a low ICC value. Together, this indicates a missing shared pattern. Also, the prediction bands width of ω_{yaw}, ω_{roll} signals are wide. This points to high variability among subjects. Narrow prediction bands of a_{ML} may be caused by a small range of motion in this direction.

Based on the observations stated above, (1) we discourage the utilization of acceleration signal other than a_{AP} in PD and CG groups, (2) instead, we recommend employing angular velocity about pitch axis.

There are some limitations that need to be mentioned. A major limitation of this study is that only two measurements for each subject were taken. On the other hand, when the same test is performed within the single session a learning curve might play an important role in the results.

Conclusion

This paper tested the suitability of acceleration and angular velocity signals for continuous analysis of the Timed Up & Go sit-to-stand transition. The intra-group common pattern and intra-group variability of signals were unveiled. A strong intra-group signal pattern was observed in ω_{pitch} in both groups and a_{AP} in the CG. In conclusion, we indicate that these signals are suitable for sit-to-stand TUG analysis.

References

[1] A. Salarian, F.B. Horak, C. Zampieri, P. Carlson-Kuhta, J.G. Nutt, K. Aminian, ITUG, a sensitive and reliable measure of mobility, IEEE Trans. Neural Syst. Rehabil. Eng. 18

(2010) 303–310. https://doi.org/10.1109/TNSRE.2010.2047606.
[2] N.A. Zakaria, Y. Kuwae, T. Tamura, K. Minato, S. Kanaya, Quantitative analysis of fall risk using TUG test, Comput. Methods Biomech. Biomed. Engin. (2015). https://doi.org/10.1080/10255842.2013.805211.
[3] N. Millor, P. Lecumberri, M. Gomez, A. Mart\'\inez-Ramirez, M. Izquierdo, Kinematic Parameters to Evaluate Functional Performance of Sit-to-Stand and Stand-to-Sit Transitions Using Motion Sensor Devices: A Systematic Review, IEEE Trans. Neural Syst. Rehabil. Eng. 22 (2014) 926–936. https://doi.org/10.1109/TNSRE.2014.2331895.
[4] A. Weiss, A. Mirelman, A.S. Buchman, D.A. Bennett, J.M. Hausdorff, Using a Body-Fixed Sensor to Identify Subclinical Gait Difficulties in Older Adults with IADL Disability: Maximizing the Output of the Timed Up and Go, PLoS One. 8 (2013). https://doi.org/10.1371/journal.pone.0068885.
[5] A. Galán-Mercant, A.I. Cuesta-Vargas, Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks, BMC Res. Notes. (2014). https://doi.org/10.1186/1756-0500-7-100.
[6] A. Sant'Anna, N. Wickström, A Symbol-Based Approach to Gait Analysis From Acceleration Signals: Identification and Detection of Gait Events and a New Measure of Gait Symmetry, IEEE Trans. Inf. Technol. Biomed. 14 (2010) 1180–1187. https://doi.org/10.1109/TITB.2010.2047402.
[7] S. Viteckova, O. Klempir, P. Dusek, R. Krupicka, Z. Szabo, E. R\r užička, Statistical analysis of the 180 degree walking turn: Common patterns, repeatability and prediction bands of turn signals, Biomed. Signal Process. Control. 56 (2020). https://doi.org/10.1016/j.bspc.2019.101689.
[8] M.W. Lenhoff, T.J. Santner, J.C. Otis, M.G.E. Peterson, B.J. Williams, S.I. Backus, Bootstrap prediction and confidence bands: a superior statistical method for analysis of gait data, Gait Posture. 9 (1999) 10–17. https://doi.org/10.1016/S0966-6362(98)00043-5.
[9] Y. Higashi, K. Yamakoshi, T. Fujimoto, M. Sekine, T. Tamura, Quantitative evaluation of movement using the timed up-and-go test, IEEE Eng. Med. Biol. Mag. 27 (2008) 38–46. https://doi.org/10.1109/MEMB.2008.919494.
[10] A. Pini, J.L. Markström, L. Schelin, Test--retest reliability measures for curve data: an overview with recommendations and supplementary code, Sport. Biomech. 0 (2019) 1–22. https://doi.org/10.1080/14763141.2019.1655089.
[11] A. Duhamel, J.L. Bourriez, P. Devos, P. Krystkowiak, A. Destée, P. Derambure, L. Defebvre, Statistical tools for clinical gait analysis, Gait Posture. 20 (2004) 204–212. https://doi.org/https://doi.org/10.1016/j.gaitpost.2003.09.010.
[12] T.K. Koo, M.Y. Li, A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research, J. Chiropr. Med. 15 (2016) 155–163. https://doi.org/10.1016/j.jcm.2016.02.012.
[13] T. Chau, S. Young, S. Redekop, Managing variability in the summary and comparison of gait data, J. Neuroeng. Rehabil. 2 (2005) 22. https://doi.org/10.1186/1743-0003-2-22.
[14] W.J. Anderst, Bootstrap prediction bands for cervical spine intervertebral kinematics during in vivo three-dimensional head movements, J. Biomech. 48 (2015) 1270–1276. https://doi.org/https://doi.org/10.1016/j.jbiomech.2015.02.054.
[15] P.C. Dixon, J. Stebbins, T. Theologis, A.B. Zavatsky, Spatio-temporal parameters and lower-limb kinematics of turning gait in typically developing children, Gait Posture. 38 (2013) 870–875. https://doi.org/10.1016/j.gaitpost.2013.04.010.

Tables

	ICC (95% confidence interval)		true coverage	
	CG	PD	CG	PD
a_V	0.34* (0.3,0.4)	0.22* (0.19,0.27)	0.86	0.80
a_{ML}	0.07* (0.06,0.1)	0.01* (0,0.02)	0.93	0.87
a_{AP}	0.69* (0.65,0.74)	0.45* (0.41,0.52)	0.86	0.87
ωyaw	-0.01 (-0.01,0)	0.06* (0.05,0.09)	0.72	0.77
ωpitch	0.67* (0.63,0.72)	0.62* (0.57,0.67)	0.86	0.74
ωroll	0.01* (0,0.03)	-0.01 (-0.01,0)	0.79	0.77

Table 1. Within group common pattern and true coverage probability
* - statistically significant difference ($p<0.05$)

Figures

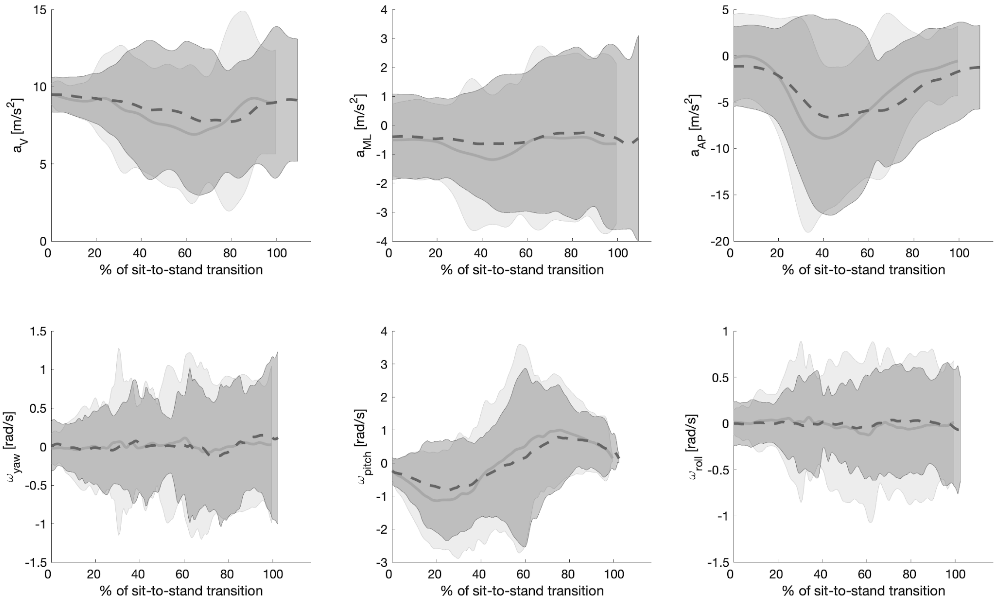


Figure 1. Kinematic data of the trunk over sit-to-stand transition in the control group and Parkinson's disease patients. Light grey area-control group prediction bands, dark grey area-Parkinson's disease patients prediction bands, solid light grey line-control group mean signal, dashed dark grey line-mean signal of Parkinson's disease patients.

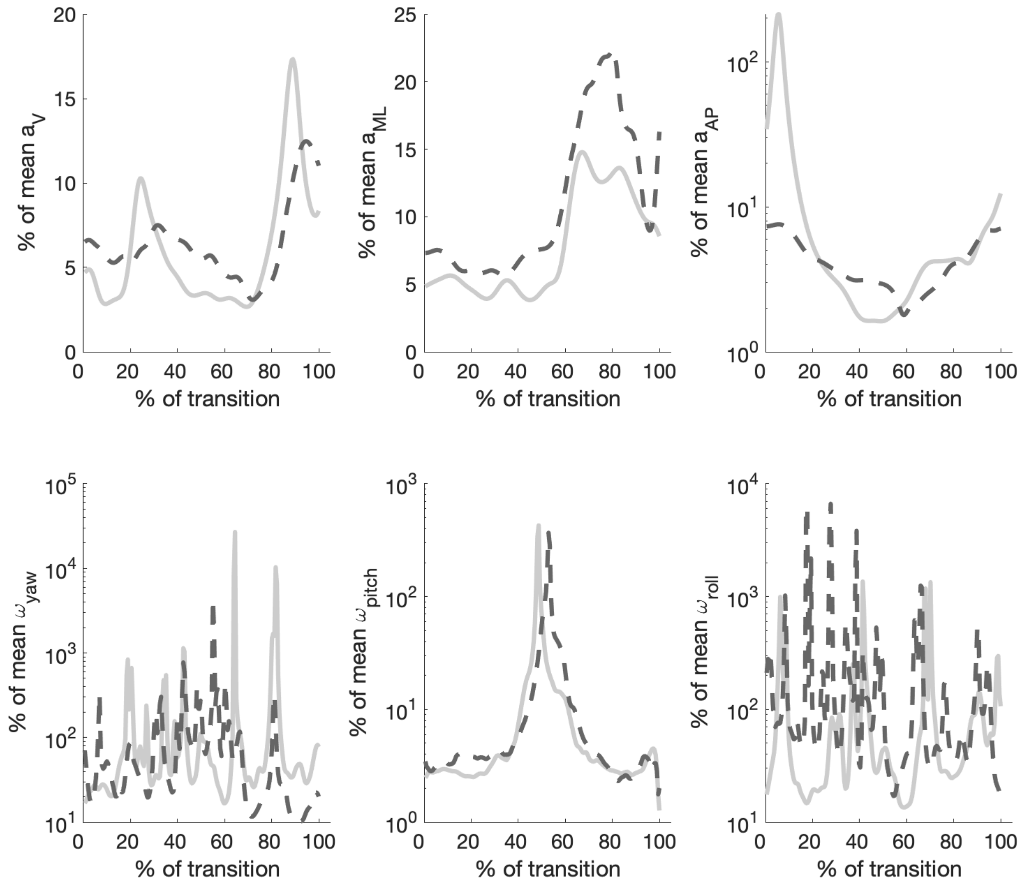


Figure 2. The ratio of prediction bands' width to signals mean in the control group and Parkinson's disease patients. Solid light grey line-control group, dashed dark grey line-Parkinson's disease patients.

Příloha C

Cíl 2: Vlastní publikace

Can sit-to-walk assessment maximize instrumented Timed Up & Go test output?

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Keywords: iTUG, Angular Rate, Sit-to-Stand, Transition, Movement

Abstract: Daily human activities commonly include standing from a seated position. In research this transition is investigated, among others, as a part of a functional Timed Up & Go test. Spatio-temporal parameters are widely used to assess the sit-to-walk transition. Usually, the parameters calculated for the sit-to-walk signal is in its entirety. Another approach primarily splits the transition into phases and then calculates parameters for individual phases separately. The objective of this work is to examine whether splitting the Timed Up & Go test into subphases provides additional value for transition assessment. In order to compare both approaches, we utilized angular rate parameters (duration, peak value, mean, variance) and analyzed their reliability. The reliability proved to be dependent on the subject group and transition phase. In addition, we compared transition parameters from the entire transition and individual phases between the two subject groups. The mean only differentiated between the subject groups in individual phases, but not is entire transition. To summarize, splitting the transition into phases turned out to be beneficial for sit-to-walk transition assessment.

1 INTRODUCTION

Standing from a seated position is a commonly performed daily activity. The sit-to-stand movement is a part of functional tests such as Timed Up & Go test. The Timed Up & Go (TUG) test is a modified timed version of the "Get-Up and Go" Test (Mathias et al., 1986). TUG involves rising from a chair, walking 3 m, turning 180°, walking back to the chair, and sitting down again. Usually, a TUG is measured as the total time it takes to perform the test.

The increasing utilization of inertial measurement units during the last decade increases the ability to separate individual TUG subcomponents (Salarian et al., 2010; Greene et al., 2010; Zakaria et al., 2015; Smith et al., 2016; Craig et al., 2017; Newman et al., 2018), i.e. sit-to-walk, walking forward, 180 degree turn, walking back to the chair and turn-to-sit, and consequently their individual assessment.

Recent studies employed two approaches to the sit-to-walk (StW) assessment. The first approach analyzed the entire StW at once. Salarian et al. (Salarian et al., 2010) tested four StW parameters (duration, peak angular velocity, mean angular velocity, and the range of trunk movement) in Parkinson disease patients and older adults. They did not reveal any difference between the tested subject groups. Also, Weiss et al. (Weiss et al., 2013) did not observe a difference in the transition measures (duration, acceleration amplitude range, median and standard deviation) of PD patients and older adult groups. Galán et al. (Galán-Mercant and Cuesta-Vargas, 2014) showed a difference in duration and acceleration-based parameters (minimal, maximal, and mean value) between frail and non-frail older adults. The second approach, Zakaria et al. (Zakaria et al., 2015) modified the StW assessment so that they divided the transition into two phases: sit-bend and bend-stand. Then, they assessed the duration, acceleration and angular rate measures (peak values, RMS) in elderly subjects with low and high risk of falls. No differences were observed in the transition phase measures for both groups. Although a number of studies utilized the instrumented TUG, only a few of them included StW assessment (Salarian et al., 2010; Weiss et al., 2013; Zakaria et al., 2015; Galán-Mercant and Cuesta-Vargas, 2014). Moreover, Millor et al. (Millor et al., 2014) noted that the angular kinematics of StW transitions in the TUG test did not yield meaningful information. None of the previous studies assessed or compared both approaches, i.e. the assessment of the entire StW and individual phases at the same time.

Reliable outcomes are crucial for the interpretation of results and the subsequent adoption in clinical practice (Smith et al., 2016). Salarian et al. (Salarian et al., 2010) examined a TUG inter-session reliability including the sit-to-walk transition of elderly subjects and patients with Parkinson's disease (PD). Their work did not provide reliability per subject groups, rather the analysed reliability of the mixed group. The results showed the poor reliability of all analysed parameters (ICC<0.5). Newman et al. (Newman et al., 2018) also assessed the intra-session reliability of a TUG including the StW transition among children with traumatic brain injury and controls. Although the reliability of the sit-to-walk parameters was assessed previously none of the previous works studied the reliability of the sit-to-walk transition with a focus on its phases.

The aim of this study is to analyse the division of the StW transition into two phases. Specifically, to examine the additional value of splitting the transition into subphases when compared to the transition assessment at once. For this purpose, we compared parameters computed for an entire StW transition and its individual phases. Then, we assessed the reliability of all computed parameters and compared the distinctiveness between the two subject groups, namely older adults and Parkinson disease patients.

2 METHODS

2.1 Participants and Protocol

Two groups of participants were enrolled in this study. The first group included 35 early untreated Parkinson disease (PD) patients (24 males, 11 females), mean age 58.6 (+-13.4). The second group, control group (CG), included 36 volunteers (32 males, 4 females), mean age 64.3 (+-9.5). All PD patients and CG were evaluated twice within one session (TUG_1, TUG_2). All subjects accomplished an extended Timed Up & Go Test (ETUG) (Wall et al., 2000). Each subject was measured while she/he rose from a chair during the ETUG, walked 10 meters, turned, walked back, and sat down again. The study was approved by the Ethics Committee of the General University Hospital in Prague, Czech Republic, and therefore performed in accordance with the ethical standards established in the 1964 Declaration of Helsinki.

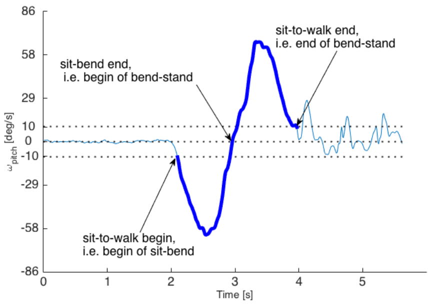

Figure 1: Plot showing pitch angular rate of one subject. Bold - sit-to-walk phase of TUG.

2.2 Data Acquisition and Processing

Xbus Master (Xsens Technologies B.V.), a lightweight (330g) and portable device using MTx units for orientation and acceleration measurements of body segments, was used for the measurement of 3-D orientation and 3-D acceleration. Kinematic data was recorded from 5 gyro-accelerometers with a data sampling rate of 100 Hz. Units were symmetrically attached to the lateral shank of each lower leg, 4 cm above the ankle joint, and the chest, 2 cm below the sternal notch.

Before further processing, the raw angular rate signal was low-pass filtered with a zero-phase second-order Butterworth filter with a 20 Hz corner frequency. In this study, we focused on the sit-to-walk (StW) transition.

In accordance with previous studies, the chest angular rate sensor was used for further processing and computation of the StW parameters. It was showed that the TUG sit-to-walk transition can be detected as the movement with an pitch angular rate higher than 10 deg/s (Higashi et al., 2008). As a negative angular rate indicates a clockwise rotation, the beginning of the StW, i.e. the beginning of the sit-bend phase, was detected from the pitch angular rate as a value less than -10 deg/s. As the crossing of the angular rate signal to zero means a rotation or direction change, the end of sit-bend phase, i.e. beginning of bend-stand phase, was detected as the crossing of the angular rate to the value zero (Figure 1). Finally, the end of StW, i.e. end of bend-stand phase, was identified as a value lower than 10 deg/s (Higashi et al., 2008).

To assess the StW we employed the mean, peak value, duration, and variance of pitch angular rate signal. All parameters were calculated for both phases and the entire transition. Thus, we calculated 12 parameters in total.

2.3 Statistical analysis

Statistical analyses were performed to examine the reliability of the StW parameters. The Intra-Class Correlation (ICC) between two measurements was used. Absolute agreement was reported. According to McGraw et al. (McGraw and Wong, 1996) reliability greater than 0.90 is considered as excellent, reliability greater than 0.75 is considered as good, greater than 0.50 is moderate, and lower than 0.50 is poor.

Next, the hypotheses on whether the StW parameters of both sit-to-walk phases are able to distinguish a healthy subject from a PD patient was tested. The Shapiro-Wilk test was used to verify the normality of parameters in each observed dataset. The assumption of a normal data distribution in the observed datasets had been rejected (significance level p=0.05). Therefore, the nonparametric Wilcoxon rank sum test was used to compare statistical significance differences in the sit-to-walk transition between PD patients and control group data. The significance level was set to $p<0.05$. All preprocessing and analyses were carried out offline using the MatLab (MatLab R2015, Mathworks, Inc., Natick, MA, USA) programming environment.

3 RESULTS

From Table 1, it can be seen that out of the four parameters, three parameters in the control group and one parameter in PD patients demonstrated poor reliability (ICC<0.50) in all three cases (entire StW, sit-bend, bend-stand). For the control group these were: duration, mean and variance. For PD patients this was only for duration. The peak value in the control group showed a higher reliability (moderate, ICC>0.50) in the bend-stand phase then in other cases (poor, ICC<0.50). The mean and variance in PD had poor reliability in the sit-bend phase and moderate (ICC>0.50) in the entire StW and bend-stand.

When comparing PD patients and the control group, the peak value, and variance were significantly different in the entire StW, sit-bend and bend-stand phases. The mean value showed the difference between the groups in the sit-bend and bend-stand phases (Figure 2). The duration did not show a difference in any of the tested cases. A significant difference in the entire StW but not sit-bend or bend-stand phases was not observed for any of utilized parameters.

4 DISCUSSION

In this work, we compared the results of the entire sit-to-walk transition to a more detailed approach with transition phases. We evaluated StW transition. Additionally, we divided the sit-to-walk transition into two phases, namely sit-bend and bend-stand, and evaluated them separately.

First, we analysed whether the StW measures calculated per phase have similar reliability as measures calculated for entire StW. The analyses were provided per subject group. Based of poor reliability results (Table 1) it can be inferred that the parameter duration of the entire StW and its phases is not suitable for StW assessment (the entirety or its parts). The results showed a higher reliability in PD patients than the CG for almost for all parameters and tested cases. This can be elucidated by the reduced concentration of the CG to perform a StW. In the PD group, some parameters (mean, variance) exhibited a lower reliability in the sit-bend phase than in other phases. In contrast to the peak parameter, mean and variance are affected by the accuracy of StW detection. Especially the detection of the StW beginning is a challenging task because the sit-bend phase may be preceded by gently bending forward and backward. Thus, a comparison of detection methods with respect to their impact to StW parameters is needed to make results more comparable across studies.

In addition, the training effect might play important role in reliability assessment of two consecutive trials. To our knowledge, the training effect of TUG subcomponents has not yet been studied.

Second, we tested whether StW phases can differentiate between PD patients and older adults better than entire StW. The present study is consistent with previous works. No differences between PD a CG were observed for duration and mean parameters computed for entire StW (Salarian et al., 2010; Weiss et al., 2013). Unlike duration, the mean parameter revealed a difference between these groups in both individual phases (sit-bend, bend-stand). Finally, we suggest that splitting StW into phases can benefit a TUG StW analysis.

Nevertheless, there are some limitations to this research study. The most important is that the sample size of the subjects was not high. However, 71 subjects proved to be sufficient for preliminary research which managed to test the basic attributes of the method proposed for further studies of TUG.

Table 1: Intra-class correlation and Wilcoxon rank sum test outcomes for the two TUG measurements. TUG_1-first TUG measurement, TUG_2-second TUG measurement, Var.-variance, *-statistically significant difference, ⋄-moderate or good intraclass correlation

	Entire StW				Sit-bend phase				Bend-stand phase			
	ICC		PD vs CG (p-value)		ICC		PD vs CG (p-value)		ICC		PD vs CG (p-value)	
	CG	PD	TUG_1	TUG_2	CG	PD	TUG_1	TUG_2	CG	PD	TUG_1	TUG_2
Time	0.12	0.40	0.06	0.38	0.17	0.48	0.06	0.42	0.09	0.33	0.14	0.16
Peak	0.42	0.73⋄	<0.01*	<0.01*	0.43	0.74⋄	<0.01*	<0.01*	0.53⋄	0.74⋄	<0.01*	0.09
Mean	0.30	0.72⋄	0.80	0.49	0.19	0.39	<0.01*	0.04*	0.44	0.53⋄	<0.01*	0.04*
Var.	0.40	0.53⋄	<0.01*	<0.01*	0.43	0.31	0.01*	<0.01*	0.37	0.70⋄	0.03*	0.02*

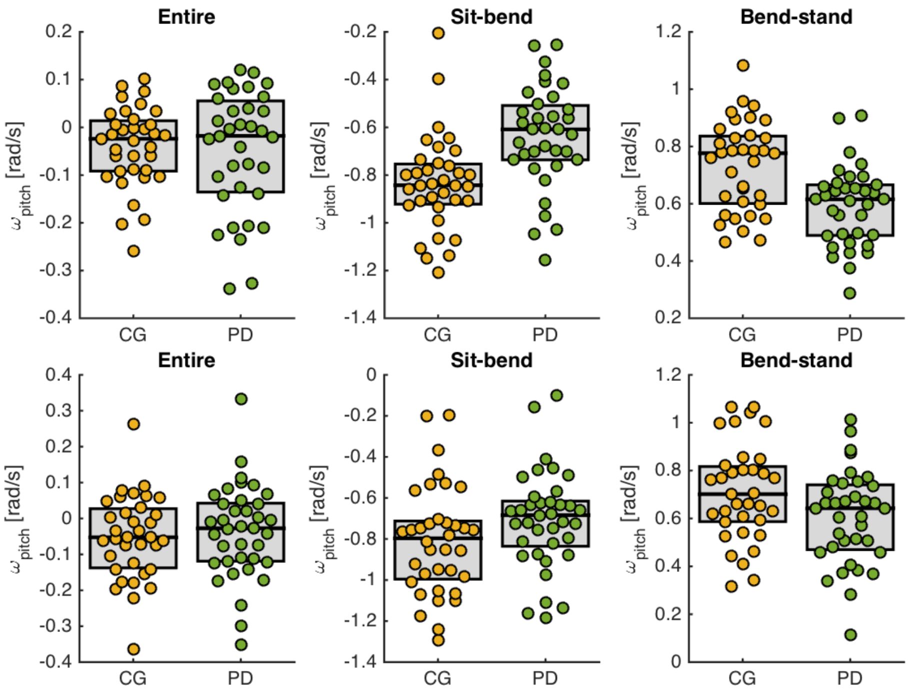

Figure 2: Scatter plots showing mean pitch angular rate differences between PD patients and control group (CG) in the entire StW, sit-bend and bend-stand phases. The top scatter plot represents the first TUG measurement (TUG_1) and the bottom represents the second TUG measurement (TUG_2).

5 CONCLUSIONS

This paper tested and compared two approaches to Timed Up & Go sit-to-walk transition analysis: the analysis of the entire transition at once and the analysis per phases. The reliability of sit-to-walk parameters was tested as well as the ability to differentiate between subject groups. We can designate that the transition splitting into phases can provide new insight into sit-to-walk transition assessment.

ACKNOWLEDGEMENTS

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REFERENCES

Craig, J. J., Bruetsch, A. P., Lynch, S. G., Horak, F. B., and Huisinga, J. M. (2017). Instrumented balance and walking assessments in persons with multiple sclerosis show strong test-retest reliability. *Journal of NeuroEngineering and Rehabilitation*, 14:43.

Galán-Mercant, A. and Cuesta-Vargas, A. I. (2014). Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks. *BMC research notes*, 7:100–100.

Greene, B. R., O'Donovan, A., Romero-Ortuno, R., Cogan, L., Scanaill, C. N., and Kenny, R. A. (2010). Quantitative falls risk assessment using the timed up and go test. *IEEE Transactions on Biomedical Engineering*, 57(12):2918–2926.

Higashi, Y., Yamakoshi, K., Fujimoto, T., Sekine, M., and Tamura, T. (2008). Quantitative evaluation of movement using the timed up-and-go test. *IEEE Engineering in Medicine and Biology Magazine*, 27(4):38–46.

Mathias, S., Nayak, U., and Isaacs, B. (1986). Balance in elderly patients: the "get-up and go" test. *Arch Phys Med Rehabil*, (1):387–9.

McGraw, K. O. and Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological Methods*, 1(1):30–46.

Millor, N., Lecumberri, P., Gomez, M., Martínez-Ramirez, A., and Izquierdo, M. (2014). Kinematic parameters to evaluate functional performance of sit-to-stand and stand-to-sit transitions using motion sensor devices: A systematic review. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 22(5):926–936.

Newman, M., Hirsch, M., Peindl, R., Habet, N., Tsai, T., Runyon, M., Huynh, T., and Zheng, N. (2018). Reliability of the sub-components of the instrumented timed up and go test in ambulatory children with traumatic brain injury and typically developed controls. *Gait and Posture*, 63:248–253. cited By 0.

Salarian, A., Horak, F., Zampieri, C., Carlson-Kuhta, P., Nutt, J., and Aminian, K. (2010). Itug, a sensitive and reliable measure of mobility. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(3):303–310.

Smith, E., Walsh, L., Doyle, J., Greene, B., and Blake, C. (2016). The reliability of the quantitative timed up and go test (qtug) measured over five consecutive days under single and dual-task conditions in community dwelling older adults. *Gait & Posture*, 43:239–244.

Wall, J., Bell, C., Campbell, S., and Davis, J. (2000). The timed get-up-and-go test revisited: Measurement of the component tasks. *J Rehabil Res Dev*, 37:109–13.

Weiss, A., Mirelman, A., Buchman, A., Bennett, D., and Hausdorff, J. (2013). Using a body-fixed sensor to identify subclinical gait difficulties in older adults with iadl disability: Maximizing the output of the timed up and go. *PLoS ONE*, 8(7). cited By 24.

Zakaria, N. A., Kuwae, Y., Tamura, T., Minato, K., and Kanaya, S. (2015). Quantitative analysis of fall risk using tug test. *Computer Methods in Biomechanics and Biomedical Engineering*, 18(4):426–437. PMID: 23964848.

Příloha D

Cíl 3: Vlastní publikace

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Original Research Article

The repeatability of the instrumented timed Up & Go test: The performance of older adults and parkinson's disease patients under different conditions

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ABSTRACT

The Timed Up & Go (TUG) test is a simple test for gait and balance that requires no special equipment and can be part of a routine clinical examination. Combined with the development of motion capture technologies, the possibilities of assessing individual TUG sub-components (i.e. sit-to-stand, gait, turn, turn-to-sit) are increasing. The clinical evaluation of an instrumented TUG requires reliable values. We analysed the intra-session repeatability of the iTUG sit-to-stand, gait and turn parameters in three conditions: (1) single, (2) cognitive dual-tasks, and (3) manual dual-tasks in older adults and Parkinson's disease (PD) patients. The repeatability coefficient (RC) was calculated for each of the 18 parameters. The repeatability varied across subject groups, the performed tasks, and the TUG subcomponent. The gait subcomponent had 6 non-repeatable spatio-temporal parameters and 2 non-repeatable parameters for the arm swing. The parameters of the turn subcomponent can be considered as non-repeatable in both groups under the manual dual-task condition and in HC under the single-task condition. When comparing PD to HC, the repeatability of the majority of the single-task parameters was higher in PD whereas lower under dual-tasks. In PD, the major part of gait parameters had a higher repeatability under single-tasks than dual-tasks. In contrast, HC exhibited better repeatability of dual-tasks than single-tasks. Repeatability can be used to assist researchers and clinicians to select adequate parameters with respect to the purpose of motion assessment.

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1. Introduction

The Timed Up & Go (TUG) test, a modified timed version of the "Get-Up and Go" Test [1], is a simple test of gait and balance that requires no special equipment and can be part of a routine clinical examination. TUG involves rising from a chair, walking 3 m, turning 180°, walking back, and sitting down again. Usually, the total time to take a TUG is measured. The TUG has been commonly used to assess mobility function [2], frailty risk [3–5], and fall risk [6].

It has been documented that attentional control plays a role in keeping normal posture and gait [7]. The dual-task paradigm, which requires these two tasks to be performed simultaneously, is increasingly used to measure performance capacity under the conditions where attention has to be divided between two tasks, in comparison with single-task conditions. In the TUG cognitive dual-task, participants complete a cognitive task (e.g., recite the days of the week in reverse order, serial subtract 3 from 100) while performing the TUG [8,9]. In the TUG manual dual-task, participants complete a manual task (e.g., carry a glass of water) [8–10]. In comparison with the single-task TUG performance, a dual-task TUG allows for assessment of functional resources and the evaluation of frailty, level of physical activity, and cognition in healthy elderly [11] as well as in patients with various neurological disorders [11,12].

Rapid progress in wearable sensors enables their utilization for automatic movement analysis in clinical settings. The TUG test supplemented with accelerometers is referred to as an instrumented TUG (iTUG), or, alternatively as a quantified TUG (QTUG). Research relating to the automatic examination of a TUG was reviewed by Sprint et al. [13]. If the iTUG is to be adopted in clinical practice it must provide an automatic detection of the TUG sub-components (i.e. sit-to-stand, gait, turn, gait, stand-to-sit) and yield reliable outcomes [14]. To obtain clinically usable data, it is necessary to evaluate TUG sub-components-derived parameters (e.g. gait or turn parameters).

Smith et al. [14] tested the reliability of gait and turn parameters in elderly subjects performing single and dual tasks. As the TUG test is used to evaluate the functional state of different subject groups, it is necessary to evaluate these parameters per subject group. Salarian et al. [15]examined the single task iTUG reliability of a mixed group consisting of elderly subjects and patients with Parkinson's disease (PD) but did not provide reliability for each subject group. Craig et al. [16] compared iTUG reliability of elderly subjects and multiple sclerosis patients focusing only on the gait sub-component. These studies which evaluated the reliability of iTUG parameters have examined data collected from inter-sessions testing from the same day [15] or over several days [14,16]. Newman et al. [17] analysed the within-session reliability of an iTUG test among ambulatory children with a diagnosis of traumatic brain injury compared to controls.

Several motor and cognitive functions deteriorate with disease progression in PD [18]. As walking depends on similar higher-level neurological systems and cognitive processes [19], gait impairment in PD is negatively affected by concurrent cognitive task [19,20].

The complexity of additional task influences the gait parameters [21]. When the gait is more compromised the importance of dual-task type on the severity of dual task interference is lowered [21]. Therefore, the additional task, cognitive or manual, increased additional sources of errors. These errors could be systematic, e.g. a learning effect, as well as random, e.g. switching prioritisation of gait or dual-tasks during the test. Previous research has never studied the repeatability of different tasks (i.e. single and dual) with two different subject groups.

Regarding the additional sources of errors, the first aim of this work is to quantify compare intra-session repeatability of iTUG sit-to-stand, gait and turn parameters in the three conditions: (1) single, (2) cognitive dual-task, and (3) manual dual-task in two subject groups, namely older adults and PD patients. The second aim is to compare repeatability of sit-to-stand, gait and turn parameters across walking conditions and subject groups.

2. Methods

2.1. Participants and data acquisition

In this observational study we consecutive from a clinic 25 patients with PD (14 M, 11 F) newly diagnosed in accordance with the MDS clinical diagnostic criteria, mean age 58.6 (SD 13.4), mean PD duration 35.9 (SD 24.5) months and 26 healthy control (HC) subjects (22 M, 4 F), mean age 64.3(SD 9.5). All PD patients were treatment-naive and were examined using the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS), from which the motor subscore (part III) was calculated (29.6, SD 14.1). Control subjects were recruited from the general community through advertisements. To be eligible for the study, controls had to be free of major neurologic disorders, gait disorders, active oncologic illness, and abuse of psychoactive substances.

All subjects completed an extended Timed Up & Go Test [22]: to rise from a chair, walk 10 m at the usual preferred walking speed, turn, walk back, and sit down again. TUG was performed twice under each of the three task conditions: (1) single-task TUG, (2) dual-task manual TUG (mTUG, carrying a glass of water), and (3) dual-task cognitive TUG (cTUG, serially subtracting 3 from a number 100 while walking, with no task prioritization. The testing order was fixed as described above (i.e. TUG, manual TUG, cognitive TUG). The seating position was standardized, the same armchair was used along all measurements. The participants were not given any instructions on how to stand up.

The Xbus Master (Xsens Technologies B.V.), a lightweight (330 g) and portable device using MTx inertial measurement units, was used for the measurement of segment movements. Kinematic data was recorded from 5 gyro-accelerometers with a data sampling rate of 100 Hz. Two Gyro-accelerometer units were symmetrically attached to the lateral aspect of both lower extremities, 4 cm above the ankle joints, two units were symmetrically attached on the dorsum of each wrist, and on the chest, 2 cm below the sternal notch (Fig. 1).

2.2. Data pre-processing

Before further processing, the raw angular rate signal was low-pass filtered with a zero-phase second-order Butterworth filter

Fig. 1 – Sensors placement.

with a 20 Hz cutoff frequency. The TUG subcomponents, namely sit-to-stand, gait, turn, and turn-to-sit, were automatically identified [15]. The gait cycles of the steady gait components were determined by an automatic algorithm as described previously [15]. The computation of gait parameters was based on previously published algorithms. The gait events were detected from angular rate of shanks in the sagittal plane [23]. The spatial parameters were estimated from angular rate of shanks in the sagittal plane and the knowledge of leg lengths [24]. Arm motion was quantified similarly to Salarian et al. [15] and Zampieri et al. [25]. Gait trunk motion parameters were also determined as previously used by Salarian et al. [15] and Zampieri et al. [25]. The turn trunk parameters were evaluated directly after automatic identification of the turn subcomponent in yaw axis. The sit-to-stand parameters were derived from the pitch [26,27]. Computed sit-to-stand, gait, and turn parameters are described in Table 1.

2.3. *Statistical analysis*

The intra-session repeatability of the iTUG parameters was estimated using the repeatability coefficient (RC) as a measure of absolute reliability [28]. The RC is the difference that exceeds only 5 % of the pair of measurements on the same subject [29].

We assumed that the difference between the measurements would be distributed around zero. The difference was tested prior to the repeatability assessment via the repeatability coefficient with a paired t-test. The significance level was set to 0.05. Zero inequality can point to a bias (e.g. learning effect) in a measurement which we did not expect due to the nature of the task.

The repeatability coefficient was calculated as

$$RC = 1.96 * \sqrt{\frac{\sum_1^n (d_2 - d_1)^2}{n}}$$

The repeatability coefficient, RC, and a 95 % confidence interval of RC was reported. The 95 % confidence interval was calculated according to Barnhart and Barborial [30]. The interpretation of RC is that the difference between any two measurements on the same subject is expected to be from -RC to RC for 95 % of subjects.

As the repeatability was computed in the same units as the assessment tool, i.e. TUG parameters, the direct comparison of RC across parameters, tests, (i.e. TUG, cTUG, mTUG) or subject groups is not relevant. Therefore, for each parameter the parameter ratio, R_P, was calculated as

$$R_P = \frac{RC_P}{mean_P}$$

where RC_P is the repeatability coefficient of the parameter and the $mean_P$ is the parameter's mean value. Better repeatability is indicated by a lower R_P value.

To compare the repeatability of parameters under different conditions, e.g. across subject groups or across tests, we employed the grand ratio, $R(C_1,C_2)$, calculated as

$$R(C_1, C_2) = \frac{R_{P,C1}}{R_{P,C2}} \quad (1)$$

where $R_{P,C1}$ is the parameter ratio of parameter P under condition C_1, e.g. R_P of PD, and $R_{P,C2}$ is the parameter ratio of parameter P under condition C_2, e.g. R_P of HC. If the value of the grand ratio equals 0, it indicates an equality of the repeatability in both conditions. If the value of the grand ratio is lower than zero, it indicates better parameter repeatability under condition C_1; if the value of the grand ratio is higher than zero, it indicates better parameter repeatability under condition C_2.

To set up levels of repeatability, we defined the threshold T as 0.05 and utilized it in the grand ratio evaluation as follows

$$\begin{cases} -T < R < T \text{......... .... repeatability does not differ under both conditions} \\ R > T \text{ ......repeatability under condition C2 is better than under condition C1} \\ R < -T \text{.....repeatability under condition C1 is better than under condition C2} \end{cases}$$

To test whether the repeatability results were influenced by outliers present in data, we removed these outliers. Outliers were detected as values which differ by three times the standard deviation or more from the mean. The outliers were removed per parameter. Meaning that when an outlier was found in some of the parameter values the corresponding subject's data was removed from this parameter across all TUG variants (TUG, cTUG, mTUG). After the removal of outliers repeatability assessment was performed once more.

All data sets were tested via the Pearson correlation coefficient for the presence of proportional error. The correlation coefficient was calculated for each parameter under all conditions as the correlation between the mean of the parameter values and difference of the parameter values.

The effect sizes for paired samples were calculated as the ratio of samples means difference divided by the standard deviation of differences. All statistical analyses were carried out using MatLab (MatLab R2010b, Mathworks, Inc., Natick, MA, USA).

3. Results

There were no significant differences between the groups in demographic characteristics of participants (Supplementary Table 1).

Table 1 – Description of outcome parameters used in the current study.

Parameter	Abbr	Description
Total Time (s)	t_T	total time taken to accomplish the iTUG
Gait sub-component		
Peak Arm Swing Velocity (deg/s)	$swing_{max}$	maximal angular rate of the upper limbs about the vertical and frontal axes
Arm Swing Range of Motion (deg)	$swing_{RoM}$	range of rotational motion about the frontal axis
Arm Swing Asymmetry (%)	$swing_A$	asymmetry of peak arm swing velocity, computed as $A = abs(peak_L - peak_R) / max(peak_L, peak_R)$
Cadence (steps/min)	cadence	number of steps per minute
Gait cycle time (s)	t_{GC}	average duration of gait cycles
Double support (%)	ds	duration of the double support phase relative to the duration of the gait cycle
Stride length (m)	$stride_L$	average length of strides
Stride velocity (m/s)	$stride_V$	average velocity of strides
Stride Time Variability (%)	$stride_{T,var}$	variability of gait cycle duration, computed as the ratio of standard deviation to mean cycle duration
Stride Length Variability (%)	$stride_{L,var}$	variability of stride length, computed as the ratio of standard deviation to mean stride length
Peak Trunk Rotation Velocity (deg/s)	$trunk_{rot,max}$	maximal angular rate of the trunk about the vertical axis
Trunk Rotation Range of Motion (deg)	$trunk_{RoM}$	range of rotational motion about the vertical axis
Turn sub-component		
Average Turning Velocity (deg/s)	$turn_{avg}$	maximal angular rate of the trunk about the vertical axis
Peak Turning Velocity	$turn_{max}$	turning velocity, computed as 180 degrees / duration of the turn
Sit-to-stand sub-component		
Average Trunk Velocity (deg/s)	$trunk_{avg}$	average angular rate of the trunk about the frontal axis
Peak Trunk Velocity (deg/s)	$trunk_{max}$	maximal angular rate of the trunk about the frontal axis
Time (s)	t_{STS}	time taken from the beginning of the iTUG to the beginning of gait
Trunk Incline (deg)	$trunk_{incl}$	maximal trunk incline

The mean and standard deviation of the two trials performed under each of the three task conditions are shown in Table 2. Repeatability coefficients accompanied by 95 % confidence intervals for all instrumented TUG parameters are shown in Table 3 and 4.

Out of 18 parameters, 9 parameters in healthy controls and 5 parameters in PD patients presented no outliers under all three TUG conditions. For HC these were: t_T, $swing_{max}$, $swing_A$, $stride_L$, $stride_V$, $stride_{L,var}$, and all turn parameters ($turn_{avg}$, $turn_{max}$, $trunk_{avg}$). For PD patients these were: $swing_{max}$, $trunk_{rot,max}$, $turn_{max}$, $trunk_{max}$, and $trunk_{incl}$. For details about the number of outliers, refer to supplementary material.

Most of the gait parameters under the single-task condition exhibited statistically significant differences between the first and second trial ($p < 0.05$) in both groups, namely $swing_{max}$, $swing_{RoM}$, cadence, t_{GC}, ds, $stride_L$, and $stride_V$. Turn parameters in the single-task condition also exhibited the same behaviour in HC ($p < 0.05$).

Under the manual dual-task condition 8 gait parameters, all turn parameters, and most of the sit-to-stand parameters exhibited a statistically significant difference between the trials ($p < 0.05$) in both groups ($swing_{max}$, $swing_{RoM}$, $swing_A$, cadence, t_{GC}, $stride_V$, $turn_{avg}$, $turn_{max}$, $trunk_{avg}$, $trunk_{max}$, $trunk_{incl}$).

Under the cognitive dual-task condition none of the parameters showed a statistically significant difference between the trials in both groups.

Out of all 3 TUG conditions, no parameter exhibited the presence of a proportional error (rho>0.70). For details refer to supplementary material.

Based on grand ratio, most of the parameters ($swing_A$, cadence, t_{GC}, ds, $stride_L$, $stride_V$, $stride_{T,var}$, $stride_{L,var}$, $trunk_{RoM}$, $turn_{avg}$, $trunk_{avg}$, t_{STS}) had better repeatability under the single-task condition compared to the cognitive dual-task condition in PD. In contrast, most of the parameters ($swing_{max}$, $swing_{RoM}$, $swing_A$, cadence, ds, $stride_L$, $stride_V$, $trunk_{RoM}$, $turn_{avg}$, $turn_{max}$, $trunk_{avg}$, $trunk_{max}$) had better repeatability under cognitive dual-task condition when compared to the single-task condition in HC.

From Table 5 most of the parameters exhibited better repeatability under the manual dual-task condition than the cognitive dual-task condition in both groups. For both groups these are: $swing_A$, cadence, t_{GC}, $stride_L$, $stride_V$, $stride_{T,var}$, $trunk_{rot,max}$, $trunk_{RoM}$, $trunk_{avg}$, and t_{STS}. Only in HC, did the $stride_{L,var}$, $turn_{avg}$, and $trunk_{incl}$ reveal the same behaviour. In only PD patients was this demonstrated by the sole parameter (ds).

When comparing the repeatability under the single-task and the manual dual-task condition, 13 parameters in HC ($swing_A$, cadence, t_{GC}, ds, $stride_L$, $stride_V$, $stride_{L,var}$, $trunk_{RoM}$, $turn_{avg}$, $turn_{max}$, $trunk_{avg}$, t_{STS}, $trunk_{incl}$), and only 8 parameters in PD patients ($swing_A$, cadence, t_{GC}, ds, $stride_V$, $turn_{max}$, $trunk_{max}$, $trunk_{incl}$) demonstrated better repeatability under the manual dual-task. The grand ratio between PD patients and HC suggests that TUG has better repeatability in PD ($swing_A$, cadence, t_{GC}, $stride_L$, $stride_V$, $stride_{T,var}$, $trunk_{rot,max}$, $trunk_{RoM}$, $turn_{avg}$, $turn_{max}$, $trunk_{avg}$, t_{STS},). Under both dual-tasks conditions, parameters of interest have better repeatability in HC (Table 5).

After outlier removal some results of the grand ratio have different signum (Table 6, bolded values). When comparing single-task and cognitive dual task conditions, the grand ratio newly indicates better repeatability under the cognitive dual-task condition for $trunk_{RoM}$ and $trunk_{avg}$ in PD and t_{GC}, t_{STS} in HC. Better repeatability of 2 parameters ($swing_{max}$, $stride_{L,var}$) in PD and 2 parameters ($swing_{RoM}$, $stride_{T,var}$) in HC switched to mTUG condition in comparison to TUG.

Trunk rotation range of motion ($trunk_{RoM}$) switched to better repeatability from mTUG condition to cTUG condition in both groups. Also, $trunk_{avg}$ in PD changed to better repeatability from the mTUG condition to the cTUG condition. In contrast, $stride_L$ and $turn_{avg}$ have improved repeatability under mTUG condition instead of cTUG.

Significant changes in repeatability after the removal of outliers can be observed in 3 parameters ($stride_{T,var}$, $stride_{L,var}$, $trunk_{avg}$) under cTUG condition and 3 parameters ($swing_{max}$, $stride_{L,var}$, t_{STS}) under mTUG condition. These cases demonstrated improved repeatability in PD patients. Detailed results of analysis of data after outlier removal are provided in supplementary materials (Supplementary Table 2 and 3).

Effect sizes of are provided in supplementary materials (Supplementary Table 4).

The repeatability of parameters under different test conditions is visualized with Bland-Altman plots (Fig. 2, 3 and 4).

4. Discussion

The current study determined the intra-session repeatability of a comprehensive set of wireless sensor measures from an instrumented Timed-Up and Go test.

Recent studies which evaluated the reliability of iTUG-derived parameters have examined inter-session data from testing on the same day [15], or from data collected at two separate time points [14,16].

Using a repeatability coefficient this study provided an assessment for intra-session repeatability for 18 gait and other TUG-derived parameters in three conditions: single task, cognitive dual-task, and manual dual-task. The extension of the evaluation of RC provides new evidence about variation in TUG performance computed in the same units as the assessment tool, i.e. TUG. Additionally, this study provides a unique comparison of intra-session repeatability for different subject groups: healthy controls and PD patients.

Based on paired *t*-test results, most of the gait parameters under the single-task and manual dual-task conditions contain systematic errors and are not repeatable as parameters differ significantly between the trials. These results are consistent between subject groups. A similar trend was exhibited by turn parameters - turn parameters of HC under TUG and turn parameters of both groups under mTUG were not repeatable. Non-repeatability of gait and turn parameters observed under TUG and mTUG whereas mostly absent under cTUG might be attributed to the learning effect. These results suggest caution when interpreting the parameters under single or manual dual-task condition.

Our findings showed that almost all examined parameters under the single-task condition revealed better repeatability in PD patients than HC. In contrast, under dual-tasks the

Table 2 – Descriptive statistics of all parameters, mean and standard deviation. bolded - statistically significant differences between both tests.

	Single-task TUG						Cognitive dual-task TUG						Manual dual-task TUG					
	HC			PD			HC			PD			HC			PD		
	trial 1	trial 2	p-value	trial 1	trial 2	p-value	trial 1	trial 2	p-value	trial 1	trial 2	p-value	trial 1	trial 2	p-value	trial 1	trial 2	p-value
t_T	24.3 (3.39)	22.7 (2.75)	<0.01	23.8 (4.80)	22.3 (4.88)	<0.01	24.5 (3.60)	24.6 (3.99)	0.65	25.6 (5.95)	25.8 (8.47)	0.23	24.3 (3.71)	23.3 (3.69)	0.16	23.7 (5.19)	23.0 (4.72)	**0.02**
Gait sub-component																		
$swing_{max}$	171 (47.4)	192 (51.0)	**<0.01**	138 (52.4)	158 (51.5)	**<0.01**	191 (57.9)	208 (57.4)	**<0.01**	135 (50.8)	141 (53.6)	0.55	116 (31.9)	123 (34.5)	**<0.01**	91.0 (38.1)	97.7 (40.1)	**<0.01**
$swing_{RoM}$	39.6 (11.2)	44.0 (13.2)	**<0.01**	29.4 (12.0)	33.0 (12.7)	**<0.01**	46.91 (14.8)	47.7 (13.4)	**<0.01**	29.6 (12.8)	31.1 (13.8)	0.22	29.9 (9.20)	32.6 (9.42)	**<0.01**	21.3 (10.7)	21.3 (10.2)	**<0.01**
$swing_A$	25.6 (14.0)	22.9 (17.7)	0.35	33.2 (22.8)	35.5 (19.1)	0.34	26.0 (17.2)	24.6 (14.1)	0.75	39.0 (20.7)	36.9 (19.4)	0.39	75.7 (8.22)	76.0 (8.72)	**<0.01**	56.3 (25.3)	60.1 (22.8)	**<0.01**
cadence	106 (6.97)	109 (6.20)	**<0.01**	110 (11.5)	112 (11.6)	**<0.01**	104 (7.27)	106 (6.01)	0.75	105 (14.5)	108 (11.8)	**0.04**	110 (7.51)	111 (7.64)	**<0.01**	114 (11.5)	114 (11.5)	**<0.01**
t_{GC}	1.13 (0.08)	1.09 (0.06)	**<0.01**	1.10 (0.12)	1.08 (0.12)	**<0.01**	1.16 (0.09)	1.13 (0.06)	0.85	1.16 (0.19)	1.12 (0.12)	0.06	1.10 (0.08)	1.08 (0.08)	**<0.01**	1.06 (0.11)	1.06 (0.11)	**<0.01**
ds	20.4 (3.57)	19.4 (3.62)	**<0.01**	18.3 (5.46)	17.2 (4.75)	**0.02**	21.3 (3.48)	21.0 (3.40)	0.10	20.3 (7.38)	19.1 (5.69)	0.06	19.7 (3.80)	19.4 (4.00)	0.08	17.4 (4.62)	17.1 (4.71)	0.15
$stride_L$	1.35 (0.14)	1.38 (0.14)	**<0.01**	1.33 (0.11)	1.35 (0.12)	**<0.01**	1.35 (0.14)	1.35 (0.14)	0.93	1.27 (0.15)	1.30 (0.14)	**0.02**	1.35 (0.16)	1.36 (0.16)	0.43	1.32 (0.13)	1.33 (0.12)	0.85
$stride_V$	120 (15.8)	126 (15.2)	**<0.01**	122 (18.5)	127 (19.9)	**<0.01**	117 (15.9)	119 (14.3)	0.76	112 (24.6)	117 (21.1)	**<0.01**	124 (18.6)	126 (18.9)	**<0.01**	125 (20.4)	127 (19.7)	**0.02**
$stride_{T,var}$	3.03 (1.01)	2.71 (0.77)	**0.04**	4.22 (7.64)	4.15 (7.92)	0.58	4.08 (1.56)	3.81 (1.74)	**0.01**	7.24 (11.01)	4.74 (8.07)	0.08	2.94 (1.73)	2.86 (1.45)	0.50	3.75 (6.51)	4.54 (6.78)	0.74
$stride_{L,var}$	13.3 (3.73)	13.6 (3.68)	0.25	14.3 (5.28)	14.4 (4.67)	0.71	13.1 (3.19)	13.8 (3.61)	0.30	14.7 (7.17)	14.0 (4.36)	0.28	12.8 (3.68)	13.1 (3.91)	0.42	13.8 (4.69)	13.2 (2.83)	0.20
$trunk_{rot,max}$	46.0 (10.0)	47.9 (11.1)	0.25	41.4 (10.9)	42.2 (11.7)	0.53	47.9 (12.0)	49.9 (11.7)	**0.05**	41.4 (12.4)	42.0 (12.9)	0.69	37.0 (7.86)	38.6 (7.93)	**<0.01**	33.9 (9.36)	34.7 (9.74)	**<0.01**
$trunk_{RoM}$	14.6 (3.17)	13.6 (3.08)	0.16	11.9 (3.45)	11.91 (2.53)	0.95	15.0 (3.95)	14.6 (2.84)	0.92	13.0 (5.44)	12.6 (3.53)	0.19	11.1 (2.35)	11.1 (2.19)	**<0.01**	10.1 (2.20)	10.3 (2.04)	**<0.01**
Turn sub-component																		
$turn_{avg}$	85.2 (13.3)	91.5 (17.9)	0.03	76.9 (17.6)	79.1 (16.5)	0.21	93.0 (20.0)	89.8 (16.2)	0.11	75.4 (20.0)	77.0 (17.3)	0.97	71.3 (11.6)	73.3 (12.4)	**<0.01**	65.5 (15.2)	64.8 (14.2)	**<0.01**
$turn_{max}$	165 (23.7)	178 (33.1)	0.05	161 (34.3)	158 (33.3)	0.60	178 (34.2)	179 (33.2)	**0.02**	154 (34.8)	159 (32.5)	0.70	139 (19.5)	144 (20.9)	**<0.01**	133 (28.9)	129 (24.5)	**<0.01**
Sit-to-stand sub-component																		
$trunk_{avg}$	41.8 (8.38)	40.5 (7.92)	0.43	32.9 (8.56)	34.9 (10.6)	0.08	45.7 (9.4)	45.1 (8.99)	0.08	33.59 (10.3)	33.4 (10.5)	0.80	29.2 (7.31)	30.7 (7.56)	**<0.01**	25.5 (8.90)	27.0 (8.17)	**<0.01**
$trunk_{max}$	93.9 (23.0)	97.9 (21.3)	0.34	78.2 (20.7)	85.4 (32.2)	0.06	109 (36.0)	113 (30.5)	**<0.01**	75.1 (22.7)	78.8 (24.66)	0.90	68.8 (13.5)	74.1 (17.1)	**<0.01**	61.7 (18.7)	64.0 (16.7)	**<0.01**
t_{STS}	1.83 (0.35)	1.89 (0.44)	0.52	2.18 (0.54)	2.11 (0.48)	0.19	1.74 (0.34)	1.87 (0.72)	0.84	2.15 (0.75)	3.80 (8.14)	0.34	2.08 (0.44)	1.95 (0.29)	0.07	2.38 (0.54)	2.28 (0.61)	0.25
$trunk_{incl}$	43.5 (6.80)	42.5 (8.69)	0.35	40.2 (8.40)	41.3 (8.29)	0.29	45.3 (8.40)	46.5 (8.48)	0.06	39.9 (7.77)	41.0 (7.99)	0.57	37.1 (6.10)	37.2 (6.73)	**<0.01**	35.8 (7.93)	35.4 (7.76)	**<0.01**

Table 3 – Repeatability of parameters under different conditions and corresponding confidence intervals. RC-repeatability coefficient, CI-confidence interval.

Param.	TUG HC RC (95 % CI)	TUG PD RC (95 % CI)	Cognitive dual-task TUG HC RC (95 % CI)	Cognitive dual-task TUG PD RC (95 % CI)	Manual dual-task TUG HC RC (95 % CI)	Manual dual-task TUG PD RC (95 % CI)
t_T	3.94 (3.09, 5.44)	3.61 (2.83, 4.98)	4.56 (3.58, 6.3)	17.5 (13.7, 24.2)	2.48 (1.95, 3.42)	2.47 (1.94, 3.42)
$swing_{max}$	54.4 (42.6, 75.0)	48.5 (38.1, 67.0)	55.1 (43.2, 76.1)	36.7 (28.7, 50.6)	39.3 (30.8, 54.3)	50.9 (39.9, 70.2)
$swing_{RoM}$	12.4 (9.76, 17.17)	10.4 (8.15, 14.35)	12.6 (9.91, 17.4)	6.31 (4.95, 8.71)	11.3 (8.89, 15.6)	12.9 (10.1, 17.9)
$swing_A$	26.3 (20.6, 36.3)	23.2 (18.2, 32.0)	22.5 (17.7, 31.1)	28.4 (22.3, 39.3)	9.88 (7.75, 13.6)	21.7 (17.0, 30.0)
cadence	8.47 (6.64, 11.7)	6.46 (5.06, 8.91)	7.58 (5.94, 10.4)	13.0 (10.2, 18.0)	3.50 (2.74, 4.83)	4.32 (3.39, 5.96)
t_{GC}	0.09 (0.07, 0.13)	0.06 (0.05, 0.09)	0.10 (0.08, 0.13)	0.23 (0.18, 0.31)	0.04 (0.03, 0.05)	0.04 (0.04, 0.06)
ds	2.66 (2.08, 3.67)	5.14 (4.03, 7.09)	1.97 (1.54, 2.72)	7.80 (6.12, 10.76)	2.05 (1.61, 2.83)	4.33 (3.39, 5.97)
$stride_L$	0.08 (0.06, 0.11)	0.07 (0.05, 0.10)	0.07 (0.06, 0.10)	0.12 (0.10, 0.17)	0.05 (0.04, 0.07)	0.07 (0.05, 0.10)
$stride_V$	15.9 (12.5, 22.0)	13.1 (10.3, 18.1)	11.9 (9.37, 16.4)	21.4 (16.8, 29.5)	7.71 (6.05, 10.6)	9.81 (7.7, 13.5)
$stride_{T,var}$	1.57 (1.23, 2.17)	1.31 (1.03, 1.81)	4.14 (3.25, 5.71)	17.8 (14.0, 24.6)	1.92 (1.50, 2.64)	8.76 (6.87, 12.1)
$stride_{L,var}$	2.33 (1.83, 3.22)	2.53 (1.98, 3.49)	3.34 (2.62, 4.61)	6.43 (5.04, 8.87)	1.79 (1.40, 2.46)	6.77 (5.31, 9.34)
$trunk_{rot,max}$	15.8 (12.4, 21.9)	12.2 (9.61, 16.9)	27.6 (21.6, 38.1)	12.8 (10.1, 17.7)	12.2 (9.63, 16.9)	9.9 (7.77, 13.6)
$trunk_{RoM}$	6.77 (5.31, 9.34)	4.10 (3.22, 5.66)	5.90 (4.63, 8.14)	8.10 (6.35, 11.1)	4.05 (3.17, 5.58)	4.48 (3.51, 6.18)
$turn_{avg}$	29.9 (23.4, 41.3)	17.0 (13.3, 23.5)	23.9 (18.8, 33.1)	20.9 (16.4, 28.9)	16.8 (13.2, 23.2)	20.7 (16.2, 28.6)
$turn_{max}$	65.4 (51.3, 90.3)	45.7 (35.8, 63.1)	42.8 (33.5, 59.1)	38.6 (30.2, 53.3)	35.8 (28.1, 49.5)	34.4 (27.0, 47.5)
$trunk_{avg}$	14.8 (11.6, 20.4)	10.6 (8.38, 14.7)	15.4 (12.1, 21.3)	14.2 (11.2, 19.7)	9.58 (7.51, 13.2)	10.3 (8.1, 14.2)
$trunk_{max}$	41.0 (32.1, 56.6)	38.1 (29.9, 52.6)	41.7 (32.7, 57.6)	20.3 (15.9, 28.0)	33.2 (26.0, 45.9)	25.5 (20.0, 35.2)
t_{STS}	0.9 (0.71, 1.25)	0.51 (0.40, 0.71)	1.40 (1.10, 1.94)	16.3 (12.8, 22.5)	0.56 (0.44, 0.78)	0.87 (0.68, 1.20)
$trunk_{incl}$	10.2 (8.05, 14.1)	9.87 (7.74, 13.6)	11.4 (8.95, 15.7)	8.89 (6.97, 12.2)	7.29 (5.72, 10.0)	7.5 (5.88, 10.3)

repeatability in HC was better than in PD. This behaviour may be attributed to lower attention in HC while performing a single task whereas dual-tasks require concentration and consequently increased the overall attention to the task. Also, Mancini et al. has shown similar trends, with HC having lower repeatability compared to PD [31].

In some cases, under dual-tasks, HC demonstrated poorer repeatability than the PD group (even if the opposite can be expected), especially in the sit-to-stand subtask. This may be affected by the slightly higher age of controls. This higher age could relate to a decrease in muscle strength and consequently to increased movement variability [32].

Lower attention to the single-task may be the reason for overall better repeatability of single-task compared to dual-tasks in HC. In PD patients the TUG gait parameters showed better repeatability than cTUG gait parameters.

Focussing on repeatable parameters ($p > 0.05$), we can observe that in the PD group the single-task TUG demonstrated predominantly better repeatability than the cognitive dual-task. This is not surprising, as the influence of movement under a cognitive load in PD has been studied by previous research [33]. The manual dual-task seems to be more repeatable in comparison to single-task and cognitive dual-task in HC. In the PD group, a significantly higher reliability under the single task than the cognitive dual-task, but not in the manual dual-task had been observed in our results.

Regarding outlier removal, it should be noted that outlier removal changed repeatability results in some cases. From an overall perspective, the results without outliers seem to be more consistent in the context of the overall results.

Both motor and non-motor symptoms are present from the earliest phase of the disease [34] and generally get worse over

Table 4 – Repeatability of parameters under different conditions and corresponding confidence intervals calculated from data without outliers. RC-repeatability coefficient, CI-confidence interval.

Param.	TUG		Cognitive dual-task TUG		Manual dual-task TUG	
	HC RC (95 % CI)	PD RC (95 % CI)	HC RC (95 % CI)	PD RC (95 % CI)	HC RC (95 % CI)	PD RC (95 % CI)
t_T	–	3.68 (2.87, 5.12)	–	6.56 (5.12, 9.13)	–	2.52 (1.96, 3.5)
$swing_{max}$	–	49.3 (38.5, 68.7)	–	37.2 (29.0, 51.7)	–	26.0 (20.3, 36.2)
$swing_{RoM}$	12.5 (9.81, 17.4)	10.5 (8.25, 14.6)	12.9 (10.0, 17.9)	6.40 (4.99, 8.9)	8.45 (6.6, 11.7)	8.81 (6.88, 12.2)
$swing_A$	–	–	–	–	–	–
cadence	7.67 (5.99, 10.6)	6.46 (5.04, 8.98)	5.55 (4.33, 7.72)	8.21 (6.41, 11.4)	3.57 (2.78, 4.96)	4.12 (3.21, 5.73)
t_{GC}	0.08 (0.06, 0.11)	0.06 (0.05, 0.09)	0.06 (0.05, 0.09)	0.10 (0.08, 0.14)	0.04 (0.03, 0.05)	0.04 (0.03, 0.06)
ds	2.71 (2.12, 3.77)	2.53 (1.98, 3.52)	1.42 (1.11, 1.98)	5.48 (4.28, 7.62)	2.02 (1.58, 2.81)	2.08 (1.63, 2.90)
$stride_L$	–	0.07 (0.06, 0.10)	–	0.07 (0.05, 0.09)	–	0.05 (0.04, 0.07)
$stride_V$	–	13.2 (10.3, 18.4)	–	13.6 (10.6, 18.9)	–	9.77 (7.63, 13.5)
$stride_{T,var}$	1.49 (1.16, 2.07)	1.32 (1.03, 1.86)	4.18 (3.26, 5.81)	3.42 (2.66, 4.8)	1.37 (1.07, 1.91)	2.49 (1.94, 3.49)
$stride_{L,var}$	–	2.20 (1.72, 3.06)	–	2.48 (1.94, 3.45)	–	1.50 (1.17, 2.09)
$trunk_{rot,max}$	16.2 (12.6, 22.5)	–	19.7 (15.4, 27.4)	–	12.4 (9.76, 17.3)	–
$trunk_{RoM}$	6.89 (5.38, 9.58)	4.18 (3.27, 5.82)	3.65 (2.85, 5.08)	4.06 (3.17, 5.65)	4.10 (3.21, 5.71)	4.57 (3.57, 6.35)
$turn_{avg}$	–	17.3 (13.5, 24.1)	–	21.0 (16.4, 29.3)	–	14.9 (11.6, 20.7)
$turn_{max}$	–	–	–	–	–	–
$trunk_{avg}$	–	10.9 (8.51, 15.1)	–	10.4 (8.12, 14.4)	–	9.81 (7.66, 13.6)
$trunk_{max}$	41.8 (32.6, 58.2)	–	32.4 (25.3, 45.2)	–	33.9 (26.5, 47.2)	–
t_{STS}	0.69 (0.54, 0.97)	0.53 (0.41, 0.74)	0.53 (0.41, 0.75)	1.05 (0.81, 1.47)	0.59 (0.46, 0.82)	0.64 (0.50, 0.90)
$trunk_{incl}$	8.58 (6.70, 11.9)	–	11.6 (9.07, 16.1)	–	7.36 (5.75, 10.2)	–

time. It has been shown that training can improve gait parameters under dual-tasks conditions [35,36]. The findings have suggested that people with PD have the potential for short-term motor skill adaptation [35] and are able to transfer gait improvement to the performance of untrained tasks [36]. However, previous studies employed exercise lasting from one 20-min session [35] to 4 weeks [36]. It has not been elucidated yet whether short-term motor skill adaptation and multiple repetition of similar task can affect intra-session performance of gait. As the order of tasks was fixed for all participants in our study, future studies should investigate the effect of task order to their repeatability.

In summary, when comparing repeatability performance across tasks, it can be asserted that neither the single task nor dual tasks exhibited proportional error. Single-task and manual dual-task gait subcomponent revealed a big portion of non-repeatable parameters. Next, evidence showed a lowered repeatability in cognitive dual tasks compared to other tasks for PD patients. When comparing the inter-group repeatability, the single task TUG can be deemed as having better repeatability in the PD group while the cognitive dual-task seems to be more variable in PD. The manual dual-task can be considered as being more reliably repeatable in HC than PD.

Some differences from previous studies dealing with reliability in TUG gait and turn parameters [14–16] may be substantiated by different walking distance covered in TUG tests. Walking distances in timed tests influence gait speed [37] and consequently turn strategy [38] and other parameters [39].

In contrast with other studies assessing the reliability of iTUG [14–16], we did not remove sensors between measurements. Removing sensors could produce random errors

Table 5 – Comparison of repeatability under different conditions.

	R(TUG, cTUG)		R(TUG,mTUG)		R(cTUG, mTUG)		R(PD, CG)		
Param.	HC	PD	HC	PD	HC	PD	TUG	cTUG	mTUG
t_T	-0.10^{TUG}	-0.77^{TUG}	0.61^{mTUG}	0.48^{mTUG}	0.78^{mTUG}	5.45^{mTUG}	-0.07^{PD}	2.67^{HC}	0.01
$swing_{max}$	0.09^{cTUG}	0.24^{cTUG}	-0.09^{TUG}	-0.39^{TUG}	-0.16^{cTUG}	-0.51^{cTUG}	0.10^{HC}	-0.04	0.64^{HC}
$swing_{RoM}$	0.11^{cTUG}	0.61^{cTUG}	-0.18^{TUG}	-0.45^{TUG}	-0.26^{cTUG}	-0.66^{cTUG}	0.12^{HC}	-0.22^{PD}	0.69^{HC}
$swing_A$	0.22^{cTUG}	-0.10^{TUG}	7.33^{mTUG}	0.81^{mTUG}	5.85^{mTUG}	1.01^{mTUG}	-0.38^{PD}	-0.16^{PD}	1.87^{HC}
cadence	0.09^{cTUG}	-0.53^{TUG}	1.47^{mTUG}	0.54^{mTUG}	1.28^{mTUG}	2.24^{mTUG}	-0.26^{PD}	0.70^{HC}	0.19^{HC}
t_{GC}	-0.07^{TUG}	-0.73^{TUG}	1.21^{mTUG}	0.46^{mTUG}	1.38^{mTUG}	4.35^{mTUG}	-0.32^{PD}	1.31^{HC}	0.03
ds	0.43^{cTUG}	-0.27^{TUG}	0.28^{mTUG}	0.15^{mTUG}	-0.11^{cTUG}	0.57^{mTUG}	1.16^{HC}	3.24^{HC}	1.40^{HC}
$stride_L$	0.13^{cTUG}	-0.44^{TUG}	0.59^{mTUG}	-0.01	0.41^{mTUG}	0.77^{mTUG}	-0.11^{PD}	0.80^{HC}	0.43^{HC}
$stride_V$	0.28^{cTUG}	-0.43^{TUG}	1.11^{mTUG}	0.36^{mTUG}	0.64^{mTUG}	1.40^{mTUG}	-0.19^{PD}	0.84^{HC}	0.26^{HC}
$stride_{T,var}$	-0.48^{TUG}	-0.90^{TUG}	-0.17^{TUG}	-0.85^{TUG}	0.59^{mTUG}	0.41^{mTUG}	-0.43^{PD}	1.85^{HC}	2.19^{HC}
$stride_{L,var}$	-0.30^{TUG}	-0.61^{TUG}	0.25^{mTUG}	-0.65^{TUG}	0.79^{mTUG}	-0.10^{cTUG}	0.02	0.81^{HC}	2.62^{HC}
$trunk_{rot,max}$	-0.40^{TUG}	-0.05	0.04	0.02	0.74^{mTUG}	0.07^{mTUG}	-0.13^{PD}	-0.45^{PD}	-0.11^{PD}
$trunk_{RoM}$	0.20^{cTUG}	-0.46^{TUG}	0.32^{mTUG}	-0.21^{TUG}	0.10^{mTUG}	0.44^{mTUG}	-0.28^{PD}	0.59^{HC}	0.21^{HC}
$turn_{avg}$	0.29^{cTUG}	-0.21^{TUG}	0.46^{mTUG}	-0.31^{TUG}	0.13^{mTUG}	-0.14^{cTUG}	-0.35^{PD}	0.05	0.37^{HC}
$turn_{max}$	0.59^{cTUG}	0.16^{cTUG}	0.50^{mTUG}	0.09^{mTUG}	-0.05	-0.06^{cTUG}	-0.25^{PD}	0.03	0.04
$trunk_{avg}$	0.06^{cTUG}	-0.26^{TUG}	0.13^{mTUG}	-0.20^{TUG}	0.06^{mTUG}	0.09^{mTUG}	-0.13^{PD}	0.25^{HC}	0.23^{HC}
$trunk_{max}$	0.15^{cTUG}	0.77^{cTUG}	-0.08^{TUG}	0.15^{mTUG}	-0.20^{cTUG}	-0.35^{cTUG}	0.09^{HC}	-0.29^{PD}	-0.13^{PD}
t_{STS}	-0.38^{TUG}	-0.96^{TUG}	0.74^{mTUG}	-0.36^{TUG}	1.79^{mTUG}	13.7^{mTUG}	-0.51^{PD}	6.08^{HC}	0.34^{HC}
$trunk_{incl}$	-0.04	0.10^{cTUG}	0.22^{mTUG}	0.15^{mTUG}	0.27^{mTUG}	0.04	0.02	-0.12^{PD}	0.08^{HC}

R(TUG, cTUG) - grand ratio of parameter in TUG and cognitive dual-task TUG (cTUG).
R(TUG,mTUG) - grand ratio of parameter in TUG and manual dual-task TUG (mTUG).
R(cTUG,mTUG) - grand ratio of parameter in cognitive dual-task TUG and manual dual-task TUG.
R(PD, CG) - grand ratio of parameter of Parkinson's disease (PD) patients and healthy controls (HC).
superscript denotes condition with better repeatability.

associated with imprecise positioning when the sensors are reattached. In this study (without removing sensors) repeatability is influenced more by subject-related errors than device-related errors.

Generally, one [40] or more [16,41,42] trials are typically performed in the measurement of movement data. In the latter case, movement parameters are derived from one selected trial [41] or are calculated as a median [16] or average [42,43] from multiple trials. Taking into consideration that measured physiologic signals are not constants, rather, they can fluctuate, even when environmental and external conditions are fixed [44], the analysis of reliability should be performed first to get meaningful results.

As Smith et al. [14] pointed out, if the iTUG is to be adopted in clinical practice it must provide reliable data. On the other hand, parameters with lower reliability should not be neglected. With regard to gait research, lower reliability, i.e. higher variability, could initiate an investigation [45]. This approach could lead to finding the origin of higher variability for different subject groups and may serve as prognostic and diagnostic tool for diseases.

The main limitation was only two TUG repetitions per condition were acquired. Therefore, in future research we recommend to determine how many TUG trials leads to improved repeatability. For these studies it should be kept in mind, that burden of increased number of tests may be unequal between subject groups. Second, only untreated PD patients were included in the study. In future research we recommend consider the potential confounds of levodopa treatment and disease severity when measuring repeatability.

In conclusion, this study tested the reliability of 18 kinematic parameters derived from 3 variants of an instrumented Timed Up & Go test, namely the single task, the cognitive dual-task, and the manual dual-task. The parameters described the movement of the upper and lower extremities, and the chest. Within session repeatability were assessed for healthy controls and Parkinson disease patients. A big portion of gait parameters of interest was assessed as non-repeatable in all iTUG conditions. Therefore, the iTUG (under single or dual task) results should be interpreted carefully.

CRediT authorship contribution statement

Slavka Viteckova: Software, Formal analysis, Writing - original draft, Visualization. **Radim Krupicka**: Formal analysis, Writing - review & editing. **Petr Dusek**: Conceptualization, Investigation, Project administration, Funding acquisition, Writing - review & editing. **Vaclav Cejka**: Investigation, Data curation. **Patrik Kutilek**: Writing - review & editing. **Jan Novak**: Data curation. **Zoltan Szabo**: Writing - review & editing. **Evžen Růžicka**: Conceptualization, Methodology, Supervision, Writing - review & editing.

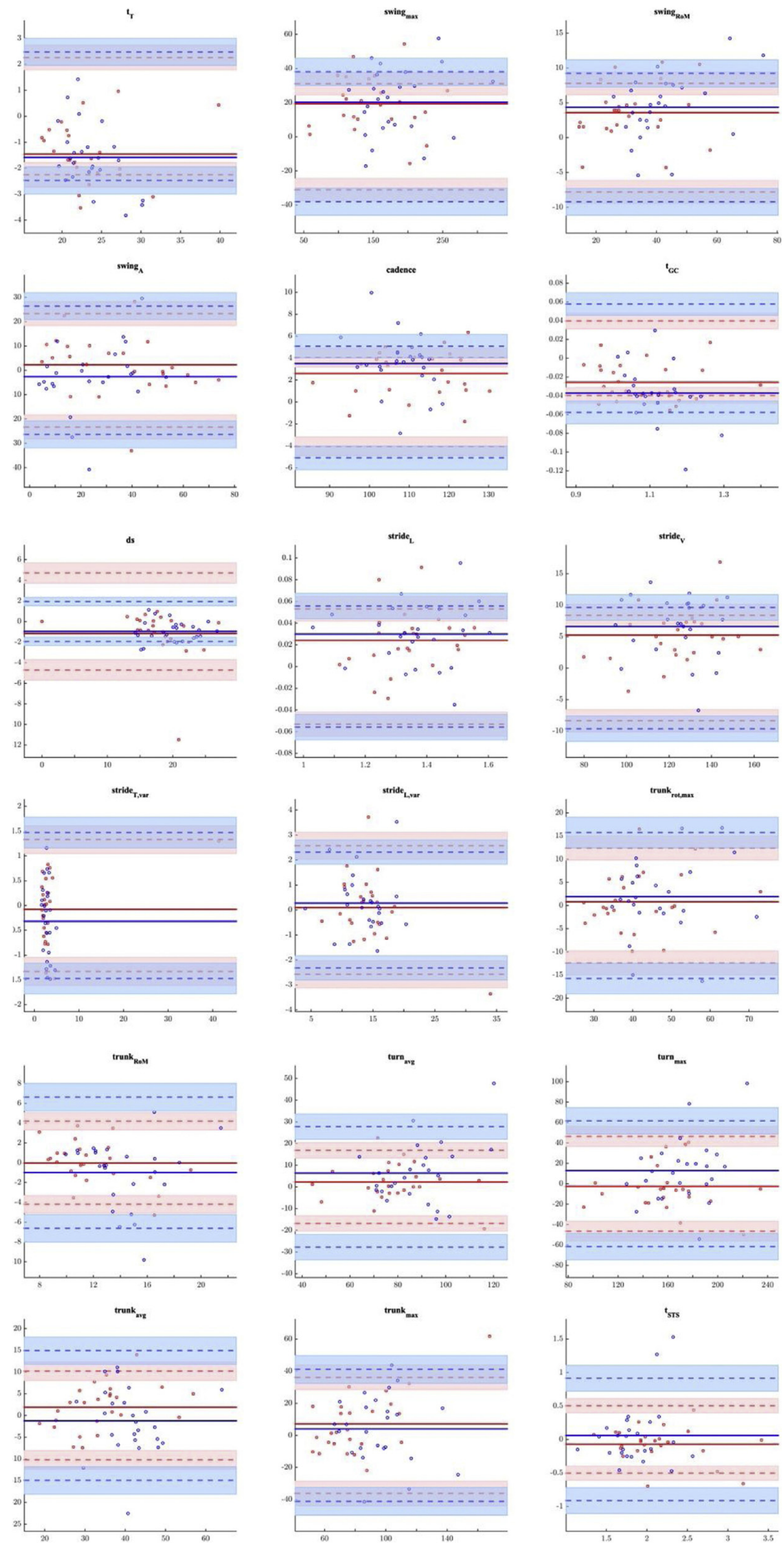

Fig. 2 – Bland-Altman plots of the agreement between two consecutive measurements of a single task TUG. Blue-healthy controls, red-PD patients, solid line-mean value, dotted lines-1.96xSD.

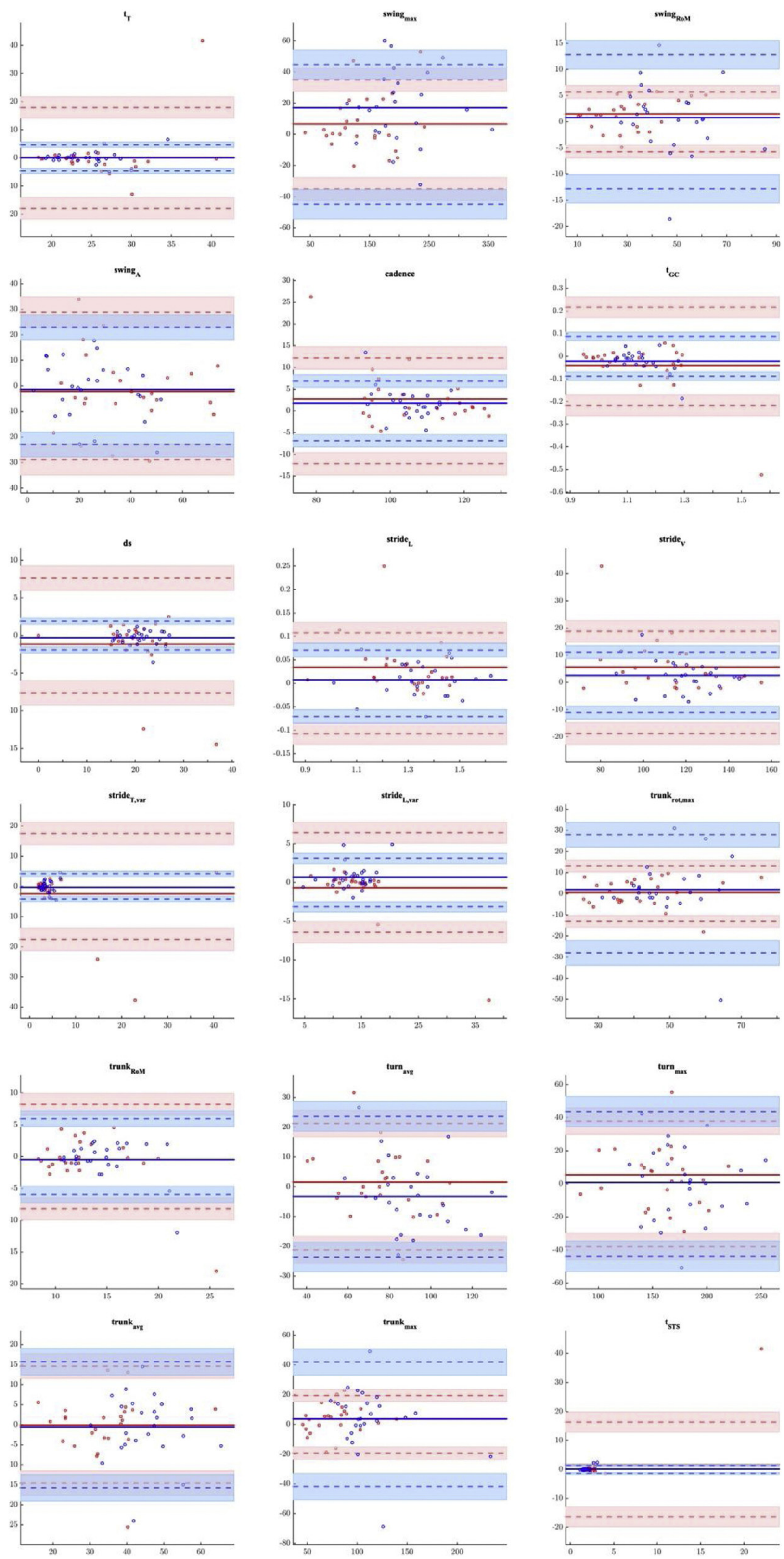

Fig. 3 – Bland-Altman plots of the agreement between two consecutive measurements of cognitive dual-task TUG. Blue-healthy controls, red-PD patients, solid line-mean value, dotted lines-1.96xSD.

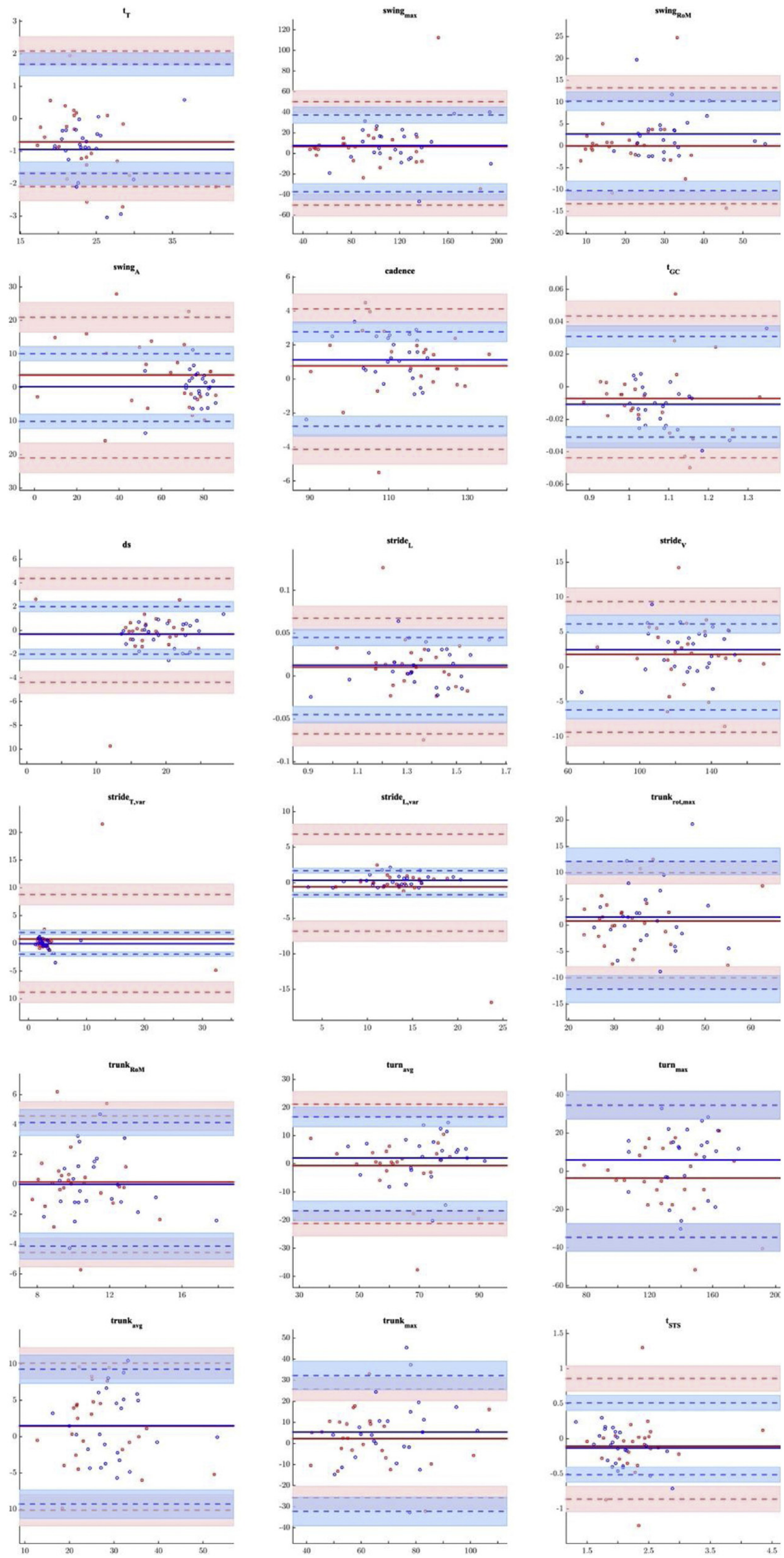

Fig. 4 – Bland-Altman plots of the agreement between two consecutive measurements of a manual dual-task TUG. Blue-healthy controls, red-PD patients, solid line-mean value, dotted lines-1.96xSD.

Table 6 – Comparison of repeatability under different conditions when outliers are removed.

	R(TUG, cTUG)		R(TUG,mTUG)		R(cTUG, mTUG)		R(PD, CG)		
Param.	HC	PD	HC	PD	HC	PD	TUG	cTUG	mTUG
t_T	–	-0.39^{TUG}	–	0.48^{mTUG}	–	1.44^{mTUG}	-0.06^{PD}	0.40^{HC}	0.02
$swing_{max}$	–	0.24^{cTUG}	–	**0.20^{mTUG}**	–	−0.04	0.13^{HC}	−0.01	**-0.14^{PD}**
$swing_{RoM}$	0.08^{cTUG}	0.61^{cTUG}	**0.12^{mTUG}**	-0.19^{TUG}	**0.03**	-0.50^{cTUG}	0.15^{HC}	-0.23^{PD}	0.59^{HC}
$swing_A$	–	–	–	–	–	–	–	–	–
cadence	0.35^{cTUG}	-0.24^{TUG}	1.19^{mTUG}	0.61^{mTUG}	0.63^{mTUG}	1.12^{mTUG}	-0.18^{PD}	0.45	0.11^{HC}
t_{GC}	**0.37^{cTUG}**	-0.38^{TUG}	0.95^{mTUG}	0.46^{mTUG}	0.43^{mTUG}	1.33^{mTUG}	-0.23^{PD}	0.68^{HC}	0.03
ds	1.02^{cTUG}	-0.50^{TUG}	0.30^{mTUG}	0.20^{mTUG}	-0.36^{cTUG}	1.42^{mTUG}	0.05	3.27^{HC}	0.14^{HC}
$stride_L$	–	−0.04	–	**0.38^{mTUG}**	–	0.43^{mTUG}	-0.12^{PD}	0.04	0.02
$stride_V$	–	-0.10^{TUG}	–	0.38^{mTUG}	–	0.52^{mTUG}	-0.18^{PD}	0.16^{HC}	0.25^{HC}
$stride_{T,var}$	-0.51^{TUG}	-0.56^{TUG}	**0.08^{mTUG}**	-0.52^{TUG}	1.22^{mTUG}	0.08^{mTUG}	-0.41^{PD}	-0.35^{PD}	0.34^{HC}
$stride_{L,var}$	–	-0.12^{TUG}	–	**0.42^{mTUG}**	–	**0.62^{mTUG}**	**-0.06^{PD}**	**-0.25^{PD}**	**-0.17^{PD}**
$trunk_{rot,max}$	-0.16^{TUG}	–	0.05	–	0.24^{mTUG}	–	-0.15^{PD}	-0.25^{PD}	-0.12^{PD}
$trunk_{RoM}$	0.92^{cTUG}	0.06^{cTUG}	0.31^{mTUG}	-0.22^{TUG}	**-0.31^{cTUG}**	**-0.26^{cTUG}**	-0.27^{PD}	0.32^{HC}	0.22^{HC}
$turn_{avg}$	–	-0.20^{TUG}	–	−0.02	–	**0.22^{mTUG}**	-0.34^{PD}	0.07^{HC}	**−0.01**
$turn_{max}$	–	–	–	–	–	–	–	–	–
$trunk_{avg}$	–	**0.05**	–	-0.11^{TUG}	–	**-0.16^{cTUG}**	-0.09^{PD}	**-0.08^{PD}**	0.16^{HC}
$trunk_{max}$	0.49^{cTUG}	0.77^{cTUG}	-0.09^{TUG}	0.15^{mTUG}	-0.39^{cTUG}	-0.35^{cTUG}	0.07^{HC}	-0.10^{PD}	-0.15^{PD}
t_{STS}	**0.20^{cTUG}**	-0.50^{TUG}	0.29^{mTUG}	-0.11^{TUG}	0.07^{mTUG}	0.76^{mTUG}	-0.35^{PD}	0.55^{HC}	**-0.06^{PD}**
$trunk_{incl}$	-0.21^{TUG}	–	0.01	–	0.27^{mTUG}	–	0.20^{HC}	-0.14^{PD}	0.04

R(TUG, cTUG) - grand ratio of parameter in TUG and cognitive dual-task TUG (cTUG).
R(TUG,mTUG) - grand ratio of parameter in TUG and manual dual-task TUG (mTUG).
R(cTUG,mTUG) - grand ratio of parameter in cognitive dual-task TUG and manual dual-task TUG.
R(PD, CG) - grand ratio of parameter of Parkinson's disease (PD) patients and healthy controls (HC).
Superscript denotes condition with better repeatability.
Bolded value indicates different signum in grand ratio of all data (see Table 4) and corresponding grand ratio of data without outliers.

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REFERENCES

[1] Mathias S, Nayak US, Isaacs B. Balance in elderly patients: the ``Get-up and go'' test. Arch Phys Med Rehabil 1986;34:119–26.

[2] Bischoff HA, Stähelin HB, Monsch AU, Iversen MD, Weyh A, von Dechend M, et al. Identifying a cut-off point for normal mobility: a comparison of the timed `up and go' test in community-dwelling and institutionalised elderly women. Age Ageing 2003;32:315–20.

[3] Kim M-J, Yabushita N, Kim M-K, Nemoto M, Seino S, Tanaka K. Mobility performance tests for discriminating high risk of frailty in community-dwelling older women. Arch Gerontol Geriatr 2010;51:192–8. http://dx.doi.org/10.1016/j.archger.2009.10.007

[4] Savva GM, Donoghue OA, Horgan F, O'Regan C, Cronin H, Kenny RA. Using timed up-and-Go to identify frail members of the older population. J Gerontol Ser A 2013;68:441–6. http://dx.doi.org/10.1093/gerona/gls190

[5] Davis DHJ, Rockwood MRH, Mitnitski AB, Rockwood K. Impairments in mobility and balance in relation to frailty. Arch Gerontol Geriatr 2011;53:79–83. http://dx.doi.org/10.1016/j.archger.2010.06.013

[6] Kenny RA, Rubenstein LZ, Martin RF, Tinetti ME. American geriatrics society and british geriatrics society and american academy of orthopaedic surgeons panel on falls prevention. Guideline for the prevention of falls in older persons. J Am Geriatr Soc 2001;49:664–72. http://dx.doi.org/10.1046/j.1532-5415.2001.49115.x

[7] Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 2002;16:1–14. http://dx.doi.org/10.1016/S0966-6362(01)00156-4

[8] Shumway-Cook A, Brauer S, Woollacott M. Predicting the probability for falls in community-dwelling older adults using the timed up & go test. Phys Ther 2000;80:896–903.

[9] Tang P-F, Yang H-J, Peng Y-C, Chen H-Y. Motor dual-task timed up & go test better identifies prefrailty individuals than single-task timed up & go test. Geriatr Gerontol Int 2015;15:204–10. http://dx.doi.org/10.1111/ggi.12258

[10] Lundin-Olsson L, Nyberg L, Gustafson Y. Attention, frailty, and falls: the effect of a manual task on basic mobility. J Am Geriatr Soc 1998;46:758–61. http://dx.doi.org/10.1111/j.1532-5415.1998.tb03813.x

[11] Giusti Rossi P, de Andrade L, Hotta Ansai J, Silva Farche AC, Carnaz L, Dalpubel D, et al. Dual-task performance: influence of frailty, level of physical activity, and cognition. J Geriatr Phys Ther 2018. Publish Ah..

[12] Christofoletti G, Andrade LP, Beinotti F, Borges G. Cognition and dual-task performance in older adults with Parkinson's and Alzheimer's disease. Int J Gen Med 2014;7:383–8. http://dx.doi.org/10.2147/IJGM.S65803

[13] Sprint G, Cook D, Weeks DL. Towards automating clinical assessments: a survey of the timed up and go (TUG). IEEE Rev Biomed Eng 2015;8:64–77.
[14] Smith E, Walsh L, Doyle J, Greene B, Blake C. The reliability of the quantitative timed up and go test (QTUG) measured over five consecutive days under single and dual-task conditions in community dwelling older adults. Gait Posture 2016;43:239–44. http://dx.doi.org/10.1016/j.gaitpost.2015.10.004
[15] Salarian A, Horak FB, Zampieri C, Carlson-Kuhta P, Nutt JG, Aminian K. ITUG, a sensitive and reliable measure of mobility. IEEE Trans Neural Syst Rehabil Eng 2010;18: 303–10. http://dx.doi.org/10.1109/TNSRE.2010.2047606
[16] Craig JJ, Bruetsch AP, Lynch SG, Horak FB, Huisinga JM. Instrumented balance and walking assessments in persons with multiple sclerosis show strong test-retest reliability. J Neuroeng Rehabil 2017;14:43. http://dx.doi.org/10.1186/s12984-017-0251-0
[17] Newman MA, Hirsch MA, Peindl RD, Habet NA, Tsai TJ, Runyon MS, et al. Reliability of the sub-components of the instrumented timed up and go test in ambulatory children with traumatic brain injury and typically developed controls. Gait Posture 2018;63:248–53. http://dx.doi.org/10.1016/j.gaitpost.2018.05.014
[18] Cooper CA, Mikos AE, Wood MF, Kirsch-Darrow L, Jacobson CE, Okun MS, et al. Does laterality of motor impairment tell us something about cognition in Parkinson disease? Parkinsonism Relat Disord 2009;15:315–7. http://dx.doi.org/10.1016/j.parkreldis.2008.07.009
[19] Kaoru Takakusaki. Functional neuroanatomy for posture and gait control. JMD 2017;10:1–17. http://dx.doi.org/10.14802/jmd.16062
[20] Raffegeau TE, Krehbiel LM, Kang N, Thijs FJ, Altmann LJP, Cauraugh JH, et al. A meta-analysis: parkinson's disease and dual-task walking. Parkinsonism Relat Disord 2019;62:28–35. http://dx.doi.org/10.1016/j.parkreldis.2018.12.012
[21] Galletly R, Brauer SG. Does the type of concurrent task affect preferred and cued gait in people with Parkinson's disease? Aust J Physiother 2005;51:175–80. http://dx.doi.org/10.1016/S0004-9514(05)70024-6
[22] Wall J, Bell C, Campbell S, Davis J. The timed Get-up-and-Go test revisited: measurement of the component tasks. J Rehabil Res Dev 2000;37:109–13.
[23] Salarian A, Russmann H, Vingerhoets FJG, Dehollain C, Blanc Y, Burkhard PR, et al. Gait assessment in Parkinson's disease: toward an ambulatory system for long-term monitoring. IEEE Trans Biomed Eng 2004;51:1434–43. http://dx.doi.org/10.1109/TBME.2004.827933
[24] Moore ST, MacDougall HG, Gracies J-M, Cohen HS, Ondo WG. Long-term monitoring of gait in Parkinson's disease. Gait Posture 2007;26:200–7. http://dx.doi.org/10.1016/j.gaitpost.2006.09.011
[25] Zampieri C, Salarian A, Carlson-Kuhta P, Aminian K, Nutt JG, Horak FB. The instrumented timed up and go test: potential outcome measure for disease modifying therapies in Parkinson's disease. J Neurol Neurosurg Psychiatry 2010;81:171–6. http://dx.doi.org/10.1136/jnnp.2009.173740
[26] Najafi B, Aminian K, Loew F, Blanc Y, Robert PA. Measurement of stand-sit and sit-stand transitions using a miniature gyroscope and its application in fall risk evaluation in the elderly. IEEE Trans Biomed Eng 2002;49:843–51. http://dx.doi.org/10.1109/TBME.2002.800763
[27] Salarian A, Russmann H, Vingerhoets FJG, Burkhard PR, Aminian K. Ambulatory Monitoring of Physical Activities in Patients With Parkinson's Disease. IEEE Trans Biomed Eng 2007;54:2296–9. http://dx.doi.org/10.1109/TBME.2007.896591
[28] Bland JM, Altman D. Statistical methods for assessing agreement between two methods of Clinical Measurement. Lancet 1986;327:307–10. http://dx.doi.org/10.1016/S0140-6736(86)90837-8
[29] Bland JM, Altman DG. Applying the right statistics: analyses of measurement studies. Ultrasound Obstet Gynecol 2003;22:85–93. http://dx.doi.org/10.1002/uog.122
[30] Barnhart HX, Barboriak DP. Applications of the repeatability of quantitative imaging biomarkers: a review of statistical analysis of repeat data sets. Transl Oncol 2009;2:231–5. http://dx.doi.org/10.1593/tlo.09268
[31] Mancini M, Salarian A, Carlson-Kuhta P, Zampieri C, King L, Chiari L, et al. ISway: a sensitive, valid and reliable measure of postural control. J Neuroeng Rehabil 2012;9:59. http://dx.doi.org/10.1186/1743-0003-9-59
[32] Kang HG, Dingwell JB. Separating the effects of age and walking speed on gait variability. Gait Posture 2008;27:572–7. http://dx.doi.org/10.1016/j.gaitpost.2007.07.009
[33] Penko AL, Streicher MC, Koop MM, Dey T, Rosenfeldt AB, Bazyk AS, et al. Dual-task interference disrupts parkinson's gait across multiple cognitive domains. Neuroscience 2018;379:375–82. http://dx.doi.org/10.1016/j.neuroscience.2018.03.021
[34] Müller B, Larsen JP, Wentzel-Larsen T, Skeie GO, Tysnes O-B, for The Parkwest Study Group. Autonomic and sensory symptoms and signs in incident, untreated Parkinson's disease: Frequent but mild. Mov Disord 2011;26:65–72. http://dx.doi.org/10.1002/mds.23387
[35] Brauer SG, Morris ME. Can people with Parkinson's disease improve dual tasking when walking? Gait Posture 2010;31:229–33. http://dx.doi.org/10.1016/j.gaitpost.2009.10.011
[36] Yogev-Seligmann G, Giladi N, Brozgol M, Hausdorff JM. A training program to improve gait while dual tasking in patients with parkinson's disease: a pilot study. Arch Phys Med Rehabil 2012;93:176–81. http://dx.doi.org/10.1016/j.apmr.2011.06.005
[37] Graham JE, Ostir GV, Kuo Y-F, Fisher SR, Ottenbacher KJ. Relationship between test methodology and mean velocity in timed walk tests: a review. Arch Phys Med Rehabil 2008;89:865–72. http://dx.doi.org/10.1016/j.apmr.2007.11.029
[38] Akram SB, Frank JS, Chenouri S. Turning behavior in healthy older adults: Is there a preference for step versus spin turns? Gait Posture 2010;31:23–6. http://dx.doi.org/10.1016/j.gaitpost.2009.08.238
[39] Forsell C, Conradsson D, Paquette C, Franzén E. Reducing gait speed affects axial coordination of walking turns. Gait Posture 2017;54:71–5. http://dx.doi.org/10.1016/j.gaitpost.2017.02.020
[40] van Iersel MB, Ribbers H, Munneke M, Borm GF, Rikkert MGO. The effect of cognitive dual tasks on balance during walking in physically fit elderly people. Arch Phys Med Rehabil 2007;88:187–91. http://dx.doi.org/10.1016/j.apmr.2006.10.031
[41] Weiss A, Mirelman A, Buchman AS, Bennett DA, Hausdorff JM. Using a body-fixed sensor to identify subclinical gait difficulties in older adults with IADL disability: maximizing the output of the timed up and go. PLoS One 2013;8. http://dx.doi.org/10.1371/journal.pone.0068885
[42] Tateuchi H, Tsukagoshi R, Fukumoto Y, Akiyama H, So K, Kuroda Y, et al. Compensatory turning strategies while walking in patients with hip osteoarthritis. Gait Posture 2014;39:1133–7. http://dx.doi.org/10.1016/j.gaitpost.2014.01.021

[43] Yang W-C, Hsu W-L, Wu R-M, Lin K-H. Immediate effects of clock-turn strategy on the pattern and performance of narrow turning in persons with Parkinson disease. J Neurol Phys Ther 2016;40:249–56. http://dx.doi.org/10.1097/NPT.0000000000000148

[44] Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 2001;82:1050–6. http://dx.doi.org/10.1053/apmr.2001.24893

[45] Schniepp R, Wuehr M, Schlick C, Huth S, Pradhan C, Dieterich M, et al. Increased gait variability is associated with the history of falls in patients with cerebellar ataxia. J Neurol 2014;261:213–23. http://dx.doi.org/10.1007/s00415-013-7189-3

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Short communication

Extended Timed Up & Go test: Is walking forward and returning back to the chair equivalent gait?

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ABSTRACT

The Timed Up & Go test (TUG) is functional test and is a part of routine clinical examinations. The instrumented Timed Up & Go test enables its segmentation to sub-tasks: sit-to-stand, walking forward, turning, walking back, stand-to-sit, and consequently the computation of task-specific parameters and sub-tasks separately. However, there are no data on whether walking forward parameters differ from the walking back parameters. This study tested the differences between walking forward and walking back in the TUG extended to 10 m for 17 spatio-temporal gait parameters. All parameters were obtained from a GAITRite® pressure sensitive walkway (CIR Systems, Inc.). The differences were assessed for healthy controls and Parkinson's disease (PD) patients. None of investigated parameters exhibited a difference between both gait subtasks for healthy subjects group. Five parameters of interest, namely velocity, step length, stride length, stride velocity, and the proportion of the double support phase with respect to gait cycle duration, showed a statistically significant difference between gait for walking forward and walking back in PD patients. Therefore, we recommend a separate assessment for walking forward and walking back rather than averaging both gaits together.

1. Introduction

The Timed Up & Go test (TUG), a modified timed version of the functional test "Get-Up and Go" (Mathias et al., 1986), is simple, requires no special equipment, and is a part of routine clinical examinations. Usually, the main parameter evaluated in clinical practice and research is the total time it takes to complete the TUG.

Along with the rapid progress in sensing technologies, the instrumented TUG and its extended modifications are increasingly being used in laboratory settings. The results of research related to the automatic examination of a TUG were extensively reviewed by Sprint et al. (2015).

The instrumented TUG enables its segmentation to sub-tasks: sit-to-stand, walking forward, turning, walking back, stand-to-sit, and consequently computation and assessment of timing and other task-specific parameters of all TUG sub-tasks separately. Despite the growing number of research focused on the sit-to-stand sub-task (Zakaria et al., 2015) and the turning subtask (Bonnyaud et al., 2015; Vervoort et al., 2016; Zakaria et al., 2015), the gait sub-task still plays an important role in TUG assessment (Ansai et al., 2018; Craig et al., 2017; Greene et al., 2012; Sheehan et al., 2014; Smith et al., 2016; Weiss et al., 2013).

The gait sub-task consists of walking forward and walking back with a turn sub-task in between. However, the evaluation of gait sub-tasks in the TUG is not standardized, some studies assessed walking forward and back separately (Ansai et al., 2018), other studies combined the walking forward and walking back actions (Weiss et al., 2013) while, the majority of studies don't report whether the computation of gait parameters is based on both gait sub-tasks combined, e.g. an average of both sub-tasks, or only one of them (Adusumilli et al., 2018; Craig et al., 2017; Greene et al., 2012; Sheehan et al., 2014; Smith et al., 2016; Spain et al., 2012). Walking forward and walking back may be differentially affected by several factors: (1) the transition from sit-to-stand to regular walking, (2) the turn task which requires the central nervous system to coordinate with body segments allowing for reorientation towards a new travel direction while maintaining dynamic body stability (Patla et al., 1999), (3) preparation for the transition to

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stand-to-sit sub-task, and (4) increasing fatigue. The effects of these factors may be even more pronounced under pathologic conditions such as neurodegenerative disorders. However, no complex study has dealt with the comparison of gait parameters before turning and after turning in a healthy population nor in patients with neurologic disorders so far. This uncertainty regarding possible differences in parameters before turning and after turning may result in inconsistent comparisons of parameter values within clinical and research measurements.

The aim of this work is to examine whether TUG gait exhibits the same spatio-temporal parameters for forward walking and walking back in older adults and Parkinson's disease patients.

2. Methods

2.1. Participants and data acquisition

In this observational study we included 26 treatment-naive patients with Parkinson's disease PD) (16 men, 10 women), mean age 58.9 (±13.2), mean PD duration 30.1 (±15.8) months, and 19 healthy control (HC) subjects (17 men, 2 women), mean age 61.7 (±8.3). PD patients were examined using the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS), from which the motor subscore (part III) was calculated (30.15 ± 12.65). Research protocol was approved by the local research Ethics Committee of the General University Hospital, Prague in accordance with the Declaration of Helsinki and an informed consent was obtained from all participants before entering the study.

As documented by Zampieri et al. (2010), the traditional TUG is not a sensitive enough tool to differentiate between untreated PD and healthy controls. In contrast, individual parameters of gait cycle measured using an instrumented TUG with an extended walking distance were shown to be sensitive enough to show gait abnormalities in early untreated PD and could potentially detect the progression of PD and their response to symptomatic and disease-modifying treatments (Zampieri et al., 2010).

Participants were instructed to perform an extended Timed Up & Go test (Wall et al., 2000) at their preferred, usual-walking speed. An extended TUG involves rising from a chair, walking 10 m in a straight line, turning 180°, walking back and sitting down in the chair. The turning point was designed by the marker on the floor. Subjects were given no instructions on which side to turn. One walking trial was performed by each subject. Gait was assessed using a 5.15 m long and 0.9 m wide instrumented walkway (Platinum model GAITRite®, CIR System Inc., Franklin, USA) placed 2.43 m from chair in the middle of the straight gait walkway. Pre-turn and post-turn gait were acquired as separate recordings on the walkway.

Previous studies showed that GAITRite is a valid and reliable tool for measuring the spatio-temporal parameters of gait (McDonough et al., 2001; Wong et al., 2014). All data was processed by experienced person using the GAITRite application software (version 4.7). We processed 17 spatio-temporal gait characteristics twice for each TUG trial: once when the participant walked forward and once when they walked back. Then, the pre-turn and post post-turn gait data was further statistically evaluated.

Parameters of interest are provided by the GAITRite walkway (thus in line with manufacturer recommendation and definitions, refer (CIR Systems Inc., 2013)). These parameters are:

- velocity (cm/s) - mean velocity of walking (distance traveled per time)
- step count (steps)
- cadence (steps/min)
- step time (s)
- step length (cm)
- cycle time (s)
- stride length (cm)
- base width (cm) - width of support base
- swing percentage (%) - a percentage of the gait cycle time
- swing time (s) - duration of swing phase
- stance percentage (%) - duration of stance phase as a percentage of the gait cycle duration
- stance time (s) - duration of stance phase
- single support percentage (%) - a percentage of the gait cycle time
- single support time (s) - duration of single support phase
- double support percentage (%) - a percentage of the gait cycle time
- double support time (s) - duration of double support phase
- stride velocity (cm/s) - ratio of stride length to stride time

All parameters were recorded and averaged for the left and right limbs.

2.2. Statistical analysis

The paired *t*-test was used to compare the spatio-temporal parameters between the left and right lower limbs, and the parameters for walking forward and back. A two sample *t*-test was used to compare the parameters of PD patients and HC. The significance level was set to 0.05. A Holm-Bonferroni correction was applied to address problems with multiple testing. Thus p-values less than 0.002 are considered significant at the Holm-Bonferroni-corrected level.

3. Results

The mean total time to complete the extended TUG was slightly higher in PD (24.56 ± 5.61 s) compared to HC (23.76 ± 3.47 s) but the difference was not statistically significant ($p = 0.94$). The comparison of spatio-temporal gait parameters between the left and right lower limbs did not show any significant difference (Table 1).

The mean value and standard deviation of each parameter for walking forward and back, and their differences are reported in Table 2; the table also shows the results of the paired *t*-test. The velocity, step length, stride length, and double support percentage were significantly different in the PD ($p < 0.002$) but not in the HC group. Namely, the PD group had decreased gait velocity and shortened steps and strides in the walking back subtasks in comparison with their forward gait. There was no significant difference between both subtasks in parameters values for the HC group. The Bland-Altman plot was used as a graphical representation of the differences between the two gaits (Fig. 1).

The results showed that neither forward walking nor walking back differed between the PD and HC group (Table 3). The comparison of differences between walking forward and walking back also did not exhibit a distinction between the PD and HC group (Table 3).

4. Discussion

The current study compared the gait parameters of walking forward to walking back from an extended Timed-Up and Go test and provided statistical assessment of 17 spatio-temporal parameters extracted from the pressure sensitive walkway. Additionally, this study contains a comparison of gait parameters for different subject groups: healthy subjects and Parkinson's disease patients.

Table 1
Comparison of gait parameters between the left and right lower limb (p-values are reported). bolded - statistically significant difference ($p < 0.05$), no p-value met Holm-Bonferroni-corrected level of p (for 17 tests performed, $p < 0.002$).

	Walking forward (p-value)		Walking back (p-value)	
	PD	HC	PD	HC
Step time	0.568	0.353	0.318	0.653
Step Length	0.224	**0.007**	0.876	0.131
Cycle Time	0.943	0.369	0.335	0.343
Stride Length	**0.010**	0.547	0.654	0.548
Support Base	0.158	0.644	0.962	0.253
Swing perc.	0.993	0.444	0.977	0.568
Swing time	0.977	0.407	0.103	0.811
Stance perc.	0.987	0.423	0.987	0.558
Stance time	0.978	1.000	0.422	0.369
Single support perc.	1.000	0.387	0.086	0.159
Single support time	0.977	0.407	0.103	0.811
Double supp. perc.	0.517	0.327	0.197	0.280
Double supp. time	0.533	0.364	0.287	0.327
Stride velocity	0.220	0.293	0.416	0.357

Our findings showed that some spatial and temporal parameters differed between walking forward and walking back and that these parameters affected healthy subjects and PD patients differently. From Table 2 it can be seen that, out of the total 17 parameters, no parameters in healthy subjects and 5 parameters in PD patients demonstrated a statistically significant difference when comparing the gait between walking forward and walking back. The absolute timing of the gait cycle seems to be preserved while the distribution of time within the gait cycle differed in PD. The parameters of healthy subjects were generally more stable within gait subtasks compared to PD patients.

The axial rigidity in PD during turning could increase lateral instability (Yang et al., 2016b). Thus, one possible explanation of the altered walking back parameters may be recovering to a stable steady gait. Another explanation may be the anticipation of the turn-to-sit transition or increased fatigue.

A number of studies segmented the TUG into subtasks (Craig et al., 2017; Greene et al., 2012; Sheehan et al., 2014; Smith et al., 2016; Zakaria et al., 2015). It has been shown that turn parameters are affected by gait velocity (Akram et al., 2010). However, the effect of the turn to the consequent gait has not yet been (to the authors' knowledge) studied. Our results suggest that its influence is not negligible and is different from a healthy and diseased population. Future studies should elucidate a mechanism for changes in gait parameters relating to the turn task and analyze the mutual relationship between instrumented TUG sub-tasks. For example, investigating the effect of the turning side with respect to lateral dominance or a more affected side of the body to walking back parameters might bring additional information. Although some research included assessment of turning strategy (Yang et al., 2016a) or the turning side (Bovonsunthonchai et al., 2014), none of the studies focused on the turning side and consecutive gait.

Contrary to our results, other recent studies demonstrated differences in spatio-temporal gait parameters between de novo, drug naıve Parkinson's disease patients and a control group (Grajić et al., 2015; Kwon et al., 2017). Both studies averaged gait data from multiple walk cycles over a pressure sensitive mat (six and 10 walks, respectively). As the current study employed a single trial, discrepant results may be justified by distinct learning effects on the gait dynamics of the control group. Moreover, the gait initiation segment before entering the mat in our and other studies might have also affected the results. Overall, our data suggests that differences between walking forward and back might be a better marker of gait abnormalities in early stages of PD than simple spatio-temporal gait parameters.

Some limitations of this study need to be mentioned. The most important is that the subjects sample size was relatively small and may not have been representative enough of larger populations of different age groups. However, the number of patients and healthy subjects proved to be sufficient for preliminary research which managed to test and evaluate the basic attributes of the TUG test. Another limit of this study is that only one trial was measured per subject. Further studies should examine repeatability of both parts of gait, i.e. walking forward and back.

In conclusion, we have documented significant differences in the parameters of walking forward and walking back subtasks of the TUG which are more pronounced in patients with Parkinson's disease compared to controls. Taking into account that both parts of gait (forward, back) might be biased by previous and ongoing sub-tasks, i.e. sit-to-stand transition, turn maneuver, and stand-to-sit transition the parameter analysis of its entirety instead of analysing the parts separately could lead to neglection of information that might be of high clinical importance. Therefore, the analysis of both gait parts should be performed separately.

Table 2
Descriptive statistics of all parameters (mean and standard deviation) and statistical evaluation of walking forward and walking back (p-value). bolded - statistically significant difference ($p < 0.05$), * differences significant at the Holm-Bonferroni-corrected level (for 17 tests performed, $p < 0.002$).

	Walking forward		Walking back		Difference between walking forward and back		*t*-test of forward vs back data (p-value)	
	PD	HC	PD	HC	PD	HC	PD	HC
Velocity (cm/s)	111.90 (25.52)	108.90 (14.35)	104.61 (23.55)	105.76 (15.50)	7.29 (6.27)	3.14 (6.07)	**<0.001***	**0.034**
Step count (steps)	5.62 (0.96)	5.80 (0.63)	6.15 (1.07)	6.10 (0.88)	−0.54 (0.66)	−0.30 (0.67)	0.136	0.162
Cadence (steps/min)	109.88 (15.07)	105.79 (8.82)	107.89 (14.37)	106.35 (9.43)	1.99 (4.45)	−0.56 (2.37)	**0.037**	0.465
Step time (s)	0.56 (0.08)	0.57 (0.05)	0.63 (0.24)	0.57 (0.05)	−0.07 (0.22)	<0.01 (0.02)	0.236	0.302
Step Length (cm)	60.45 (7.60)	61.5 (4.75)	57.61 (7.33)	59.48 (4.95)	2.84 (1.51)	2.01 (2.40)	**<0.001***	**0.007**
Cycle Time (s)	1.12 (0.16)	1.14 (0.11)	1.19 (0.27)	1.14 (0.10)	−0.07 (0.21)	<0.01 (0.04)	0.187	0.258
Stride Length (cm)	120.92 (15.12)	123.16 (9.47)	115.44 (14.83)	119.58 (9.96)	5.48 (2.93)	3.58 (4.60)	**<0.001***	**0.007**
Support Base (cm)	9.32 (3.02)	10.25 (2.51)	9.98 (2.65)	9.87 (2.69)	−0.66 (1.57)	0.38 (1.03)	0.368	0.112
Swing perc. (%)	37.31 (2.43)	37.10 (2.35)	35.27 (3.56)	36.98 (1.91)	2.04 (3.17)	0.12 (1.82)	**0.008**	0.181
Swing time (s)	0.41 (0.05)	0.42 (0.04)	0.41 (0.04)	0.42 (0.03)	0.01 (0.02)	<0.01 (0.03)	0.071	0.346
Stance perc. (%)	62.71 (2.43)	62.92 (2.35)	64.73 (3.56)	63.03 (1.92)	−2.02 (3.16)	−0.11 (1.82)	**0.007**	0.185
Stance time (s)	0.70 (0.12)	0.72 (0.08)	0.78 (0.24)	0.72 (0.08)	−0.08 (0.21)	<0.01 (0.02)	0.126	0.247
Single support perc.(%)	37.37 (2.34)	37.26 (2.02)	35.24 (3.62)	36.96 (1.90)	2.13 (3.16)	0.29 (1.35)	**0.006**	0.172
Single support time (s)	0.41 (0.05)	0.42 (0.04)	0.41 (0.04)	0.42 (0.03)	0.01 (0.02)	<0.01 (0.03)	0.071	0.346
Double supp. perc. (%)	24.73 (4.51)	26.66 (7.98)	28.88 (5.72)	26.45 (3.93)	−4.15 (4.30)	0.21 (7.11)	**0.001***	0.306
Double supp. time (s)	0.28 (0.09)	0.30 (0.08)	0.36 (0.17)	0.30 (0.07)	−0.08 (0.14)	<0.01 (0.06)	**0.033**	0.234
Stride velocity (cm/s)	112.12 (25.27)	108.36 (14.23)	101.86 (25.46)	106.35 (15.49)	10.26 (11.90)	2.01 (5.59)	**0.001***	0.051

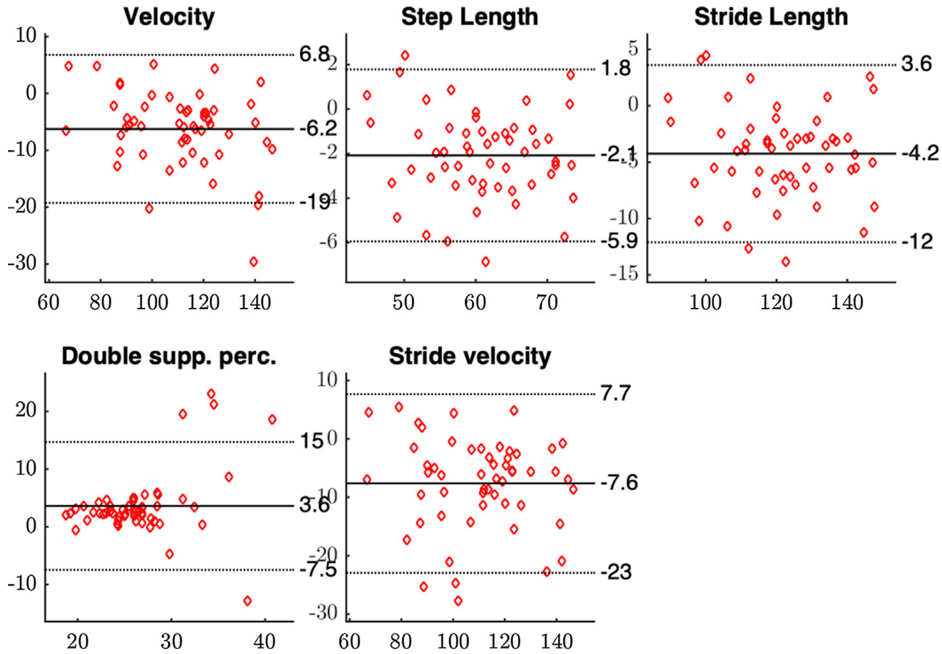

Fig. 1. Bland-Altman plots showing the differences between walking forward and walking back vs. the mean of the two gait subtasks in PD. The x-axis represents the parameter mean of walking forward and walking back; y-axis represents the parameter difference between walking forward and walking back (a positive value denotes a higher value for walking back); solid line: mean difference of all subjects, dotted lines: confidence interval limits for mean difference (±1.96SD).

Table 3
Comparison of PD patients and healthy controls (p-value). bolded - statistically significant difference ($p < 0.05$), * differences significant at the Holm-Bonferroni-corrected level (for 17 tests performed, $p < 0.002$).

	Walking forward (p-value)	Walking back (p-value)	Difference between walking forward and back (p-value)
Velocity	0.647	0.853	**0.031**
Step count	0.469	0.858	0.244
Cadence	0.296	0.685	**0.017**
Step time	0.579	0.308	0.121
Step Length	0.599	0.341	0.121
Cycle Time	0.641	0.470	0.122
Stride Length	0.571	0.296	0.120
Support Base	0.282	0.888	**0.010**
Swing perc.	0.770	0.064	**0.014**
Swing time	0.566	0.161	0.355
Stance perc.	0.779	0.065	**0.014**
Stance time	0.700	0.289	0.077
Single support perc.	0.860	0.065	**0.011**
Single support time	0.566	0.161	0.355
Double supp. perc.	0.307	0.117	**0.022**
Double supp. time	0.421	0.173	**0.020**
Stride velocity	0.563	0.498	**0.003**

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Conflict of interest

The authors declare no conflict of interest.

References

Adusumilli, G., Lancia, S., Levasseur, V.A., Amblee, V., Orchard, M., Wagner, J.M., Naismith, R.T., 2018. Turning is an important marker of balance confidence and walking limitation in persons with multiple sclerosis. PLoS One 13, 1–10. https://doi.org/10.1371/journal.pone.0198178.

Akram, S.B., Frank, J.S., Chenouri, S., 2010. Turning behavior in healthy older adults: Is there a preference for step versus spin turns? Gait Posture 31, 23–26. https://doi.org/10.1016/j.gaitpost.2009.08.238.

Ansai, J.H., de Andrade, L.P., Nakagawa, T.H., Rebelatto, J.R., 2018. Performances on the Timed Up and Go Test and subtasks between fallers and non-fallers in older adults with cognitive impairment. Arq. Neuropsiquiatr. 76, 381–386.

Bonnyaud, C., Pradon, D., Vuillerme, N., Bensmail, D., Roche, N., 2015. Spatiotemporal and kinematic parameters relating to Oriented gait and turn performance in patients with chronic stroke. PLoS One 10. https://doi.org/10.1371/journal.pone.0129821.

Bovonsunthonchai, S., Hiengkaew, V., Vachalathiti, R., 2014. Temporospatial analysis: gait characteristics of young adults and the elderly in turning while walking. Int. J. Ther. Rehabil. 22, 129–134 https://doi.org/10.12968/ijtr.2015.22.3.129.

Craig, J.J., Bruetsch, A.P., Lynch, S.G., Horak, F.B., Huisinga, J.M., 2017. Instrumented balance and walking assessments in persons with multiple sclerosis show strong test-retest reliability. J. Neuroeng. Rehabil. 14, 43. https://doi.org/10.1186/s12984-017-0251-0.

Grajić, M., Stanković, I., Radovanović, S., Kostić, V., 2015. Gait in drug na{\"\i}ve patients with de novo Parkinson's disease – altered but symmetric. Neurol. Res. 37, 712–716. https://doi.org/10.1179/1743132815Y.0000000043.

Greene, B.R., Doheny, E.P., Walsh, C., Cunningham, C., Crosby, L., Kenny, R.A., 2012. Evaluation of falls risk in community-dwelling older adults using body-worn sensors. Gerontology 58, 472–480.

Kwon, K.-Y., Lee, H.M., Kang, S.H., Pyo, S.J., Kim, H.J., Koh, S.-B., 2017. Recuperation of slow walking in de novo Parkinson's disease is more closely associated with increased cadence, rather than with expanded stride length. Gait Posture 58, 1–6. https://doi.org/10.1016/j.gaitpost.2017.06.266.

Mathias, S., Nayak, S.L., 1986. U.B.Balance in elderly patients: the "get-up and go" test. Arch. Phys. Med. Rehabil. 34, 119–126.

McDonough, A.L., Batavia, M., Chen, F.C., Kwon, S., Ziai, J., 2001. The validity and reliability of the GAITRite system's measurements: a preliminary evaluation. Arch. Phys. Med. Rehabil. 82, 419–425. https://doi.org/10.1053/apmr.2001.19778.

Patla, A.E., Adkin, A., Ballard, T., 1999. Online steering: coordination and control of body center of mass, head and body reorientation. Exp. Brain Res. 129, 629–634. https://doi.org/10.1007/s002210050932.

Sheehan, K.J., Greene, B.R., Cunningham, C., Crosby, L., Kenny, R.A., 2014. Early identification of declining balance in higher functioning older adults, an inertial sensor based method. Gait Posture 39, 1034–1039 https://doi.org/https://doi.org/10.1016/j.gaitpost.2014.01.003.

Smith, E., Walsh, L., Doyle, J., Greene, B., Blake, C., 2016. The reliability of the quantitative timed up and go test (QTUG) measured over five consecutive days under single and dual-task conditions in community dwelling older adults. Gait Posture 43, 239–244. https://doi.org/10.1016/j.gaitpost.2015.10.004.

Spain, R.I., George, R.J., Salarian, A., Mancini, M., Wagner, J.M., Horak, F.B., Bourdette, D., 2012. Body-worn motion sensors detect balance and gait deficits in people with multiple sclerosis who have normal walking speed. Gait Posture 35, 573–578. https://doi.org/10.1016/j.gaitpost.2011.11.026.

Sprint, G., Cook, D., Weeks, L.D., 2015. towards automating clinical assessments: a survey of the timed up and go (TUG). IEEE Rev. Biomed. Eng. 8, 64–77.

Vervoort, D., Vuillerme, N., Kosse, N., Hortobágyi, T., Lamoth, C.J.C., 2016. Multivariate analyses and classification of inertial sensor data to identify aging effects on the timed-Up-and-Go test. PLoS One 11. https://doi.org/10.1371/journal.pone.0155984.

Wall, J., Bell, C., Campbell, S., Davis, J., 2000. The timed get-up-and-go test revisited: measurement of the component tasks. J. Rehabil. Res. Dev. 37, 109–113.

Weiss, A., Mirelman, A., Buchman, A.S., Bennett, D.A., Hausdorff, J.M., 2013. Using a body-fixed sensor to identify subclinical gait difficulties in older adults with IADL disability: maximizing the output of the timed up and go. PloS One 8. https://doi.org/10.1371/journal.pone.0068885.

Wong, J.S., Jasani, H., Poon, V., Inness, E.L., McIlroy, W.E., Mansfield, A., 2014. Inter- and intra-rater reliability of the GAITRite system among individuals with sub-acute stroke. Gait Posture 40, 259–261. https://doi.org/10.1016/j.gaitpost.2014.02.007.

Yang, W.-C., Hsu, W.-L., Wu, R.-M., Lin, K.-H., 2016a. Immediate effects of clock-turn strategy on the pattern and performance of narrow turning in persons with Parkinson disease. J. Neurol. Phys. Ther. 40, 249–256. https://doi.org/10.1097/NPT.0000000000000148.

Yang, W.-C., Hsu, W.-L., Wu, R.-M., Lu, T.-W., Lin, K.-H., 2016b. Motion analysis of axial rotation and gait stability during turning in people with Parkinson's disease. Gait Posture 44, 83–88. https://doi.org/10.1016/j.gaitpost.2015.10.023.

Zakaria, N.A., Kuwae, Y., Tamura, T., Minato, K., Kanaya, S., 2015. Quantitative analysis of fall risk using TUG test. Comput. Methods Biomech. Biomed. Eng. https://doi.org/10.1080/10255842.2013.805211.

Zampieri, C., Salarian, A., Carlson-Kuhta, P., Aminian, K., Nutt, J.G., Horak, F.B., 2010. The instrumented timed up and go test: potential outcome measure for disease modifying therapies in Parkinson's disease. J. Neurol. Neurosurg. Psych. 81, 171–176. https://doi.org/10.1136/jnnp.2009.173740.

Příloha F

Cíl 5: Vlastní publikace

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Short communication

Statistical analysis of the 180 degree walking turn: Common patterns, repeatability and prediction bands of turn signals

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ABSTRACT

Turning is an essential movement and has been shown to be a relevant measure for differentiating pathologies. Nowadays, turn analyses utilizing inertial measurement units (IMU) have expanded. Although several IMU-based turn metrics exist, there is no information on the repeatability of turn signals and on the existence of signal patterns shared across subjects. Also, the variability of IMU signals within various subject groups has not been estimated yet. This paper presents an analysis of turn angular velocity and acceleration provided by IMU and tests them for repeatability, patterns, and variability within groups of healthy and diseased subjects. Intra-class correlation and methods for estimating prediction bands, namely the Gaussian point-by-point and bootstrap method, were employed to analyze turn signals from Parkinson disease patients and a control group. The yaw angular velocity demonstrated the highest repeatability in both groups as well as reliability of a shared pattern ($p = 0.79$ and 0.86). The bootstrap method showed wider bands and higher true coverage in comparison to its Gaussian counterpart. From the results of the performed analysis, we recommend the bootstrap method for determining prediction bands. We also recommend the yaw angular velocity as the signal to be assessed in turn analysis.

1. Introduction

Turning is an essential movement which is required in nearly every daily activity task. Turning is a challenging task and there is evidence that turns are associated with a higher risk of falling [1]. Previous studies indicate that quantitative parameters of turning are useful markers that are sensitive to age effects and different pathologies. Namely, they were shown to differentiate healthy elderly from those with a mild cognitive impairment [2] or PD patients [3], and elderly adults with daily living disabilities [4]. A need to consider turning manoeuvres in routine clinical practice has been suggested [5].

Widely used data acquisition devices output continuous curves. These curves are expressed as a function of the time or percentage of turn. Usually, a single parameter is computed from the continuous curve. Extracted parameters are typically a minimal, maximal, mean value, or the value at a specific event (e.g. at heel strike). In comparison to single parameter analysis, analysis of the continuous curve is more informative [6].

In research and clinical practice, four types of issues related to curve analysis are encountered. The first issue concerns whether the curves of subject groups have the same pattern. This is important in selecting parameters for quantification of the turning manoeuvre because the quantification of curves with different patterns may not be adequate. Moreover, when the curves have a similar pattern then they can be processed to build the mean curve which serves as a representative curve for a given subject group.

The second issue concerns the repeatability of curves. When a turn task is performed repeatedly, e.g. within one session or an inter-session, the recorded curves should be characteristic for the subject to represent a usable parameter.

The third problem deals with classification of individual curves, i.e. deciding whether the subject's curve belongs to specific population (e.g. subject groups) or not. Statistical methods used in analysis of single parameters are not suitable for continuous curves. It has been shown that prediction bands are an adequate statistical tool

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when applied to continuous curves of gait [7–10], cervical spine movement [11], and scapulo-humeral coordination [12]. Using prediction bands, the range of likelihood kinematics of subject groups can be defined. Determination of a “normal” range is necessary for researchers and clinicians to classify whether assessed curves belong to the same population as the training curves.

Finally, the fourth problem covers the comparison of subject groups. The comparison of the mean differences between subject groups can be useful to designate attractive parts which differentiate between the groups. Such differences might lay a foundation for further quantitative analysis.

An increasing amount of research involving the 180° walking turn [13–17] utilizes inertial measurement units to acquire data about the translational and/or rotational component of movement. However, the suitability, i.e. common pattern, of various turn signals for continuous analysis have not been explored yet. Furthermore, the intra-subject repeatability of curves has not been determined. Regarding the confidence bands of the walking turn manoeuvre, there was only one study that presented confidence bands for lower limbs kinematics [18] and kinetics [19] in typically developing children. It would be beneficial to researchers if a range of normal kinematics, namely angular velocity and acceleration, were established for the 180° turn manoeuvre.

Based on the highlighted problems, we address the following aims: (1) to identify which signals are suitable for walking turn analysis (2) to calculate prediction bands for walking turn signals, (3) provide reference curves for two subject groups, namely older adults and Parkinson disease patients, and (4) suggest promising turn segments for further assessment.

2. Methods

2.1. Participants and data acquisition

In the study we included 27 older healthy volunteers (24 males, 3 females), mean age 64.2 (SD 8.3) years without history of neurological disorder, and 24 mild treatment-naive Parkinson disease (PD) patients (15 males, 9 females), mean age 59.2 (SD 11.9) years. The study was approved by the Ethics Committee of the General University Hospital in Prague, Czech Republic, and therefore performed in accordance with the ethical standards established in the 1964 Declaration of Helsinki. Written, informed consent was obtained prior to data collection.

All subjects performed an instrumented extended Timed Up & Go Test (TUG) twice [20] wearing three gyro-accelerometers (MTx units, Xsens Technologies B.V.). The participant got up from a chair, walked 10 m straight, performed a 180° turn at the designated spot, walked back to the seat and sat in the chair. Gyro-accelerometer units were mounted on the subject’s segments in compliance with the study by Salarian et al. [21]: symmetrically attached on the lateral shank of each lower leg, 4 cm above the ankle joint, and the chest, 2 cm below the sternal notch.

2.2. Data analysis

2.2.1. Preprocessing

Kinematic data was collected at 120 Hz and low-pass filtered at 20 Hz with a zero-phase second-order Butterworth filter. An automated analysis algorithm identified the turn component of the TUG [21]. From the automatic analysis, we employed trunk angular velocity and acceleration signals for further analysis. All continuous turn signals were time-aligned to the same length. The length equalled 300 samples which is an average length of all the analysed turn curves. For angular velocity and acceleration, all analyses were performed in 3 dimensions, namely angular velocity about the roll-axis (ω_{roll}), pitch-axis (ω_{pitch}), and yaw-axis (ω_{yaw}); vertical (a_V), medio-lateral (a_{ML}), and antero-posterior (a_{AP}) acceleration were analysed. All data analysis was carried out in Matlab 2015.

2.2.2. Common curve patterns

Assessment of common curve patterns within a subject group can be switched to an inter-subject reliability task. A widely used index in reliability analysis is Intraclass Correlation Coefficient (ICC). It can be assumed that the analysed measurements have similar characteristics. Thus, the two-way random effects model was selected. As we used single measurements as the basis (not mean of k-measurements) we utilized the “single rater” ICC type. Based on the assumption that inter-subjects’ curves share the same pattern plus systematic error, we employed consistency relationship between curves. In summary, the two-way random effects, consistency, single measurements for ICC was used. For details on ICC selection refer guidelines by Koo and Li [22]. ICC was computed for each point along the entire turning curve.

2.2.3. Intra-subject repeatability

It can be assumed that the curve representing the turn movement of one subject can be replicated when the subject moves repeatedly. The extent of replicability is represented by reliability. As employed by Duhamel et al. [8] to assess intra-subject repeatability of gait curves, we employed ICC to assess the repeatability of turn curves. As we compared two curves from one subject, the suitable ICC model is a two-way mixed-effects model. The single measurement was used as the basis, thus, the “single rater” type was utilized. We considered absolute agreement between the measurements to be expected. In summary, we employed two-way mixed effects, absolute agreement, and single measurement for reliability analysis [22].

2.2.4. Prediction bands

The 95% prediction bands (PB) were estimated using two methods: the bootstrap method and Gaussian point-by-point method. The bands via bootstrap were computed with 1000 bootstrap samples. Details of the bootstrap technique can be found elsewhere [7], the implementation is available at https://github.com/vitecsla-fbmi/predictionBands/. The true coverage probability of each technique was determined by cross-validation [7].

2.2.5. Groups comparison

Data from both subject groups were compared. Effect size was estimated for each point along the entire turning curve by Cohen’s d [23]. A graphical representation of the results is provided via the colour bars, where values less than 0.20, 0.50, 0.80 and 1 represents very small, small, medium, and large effect size.

3. Results

3.1. Common curve patterns

The inter-subject reliability of all acceleration curves was poor in both subject groups ($\rho < 0.50$). For angular velocity signals the reliability varies from poor ($\rho < 0.50$) to good ($0.90 > \rho > 0.75$). Yaw angular velocity of both groups demonstrated good reliability ($\rho = 0.79$ for PD, $\rho = 0.86$ for CG). For details refer to Table 1.

3.2. Intra-subject repeatability

The intra-subject reliability of the yaw angular velocity varies from moderate ($\rho > 0.50$) to excellent ($\rho > 0.90$). Other angular velocity curves showed reliability ranging from poor to good in

Table 1
Inter-subject reliability of acceleration and angular velocity signals. The intra-class correlation (p) and 95% confidence interval is reported. * **good reliability.** Abbreviations: CG = Control group; PD = Parkinson's disease patients.

	a_V	a_{ML}	a_{AP}	ω_{yaw}	ω_{pitch}	ω_{roll}
CG	0.20 (0.18–0.24)	0.07 (0.05–0.09)	0.26 (0.24–0.31)	**0.86*** (0.84–0.88)	0.09 (0.07–0.11)	0.21 (0.19–0.25)
PD	0.10 (0.08–0.12)	0.01 (0–0.02)	0.25 (0.23–0.3)	**0.79*** (0.77–0.82)	0.02 (0.01–0.03)	0.16 (0.14–0.2)

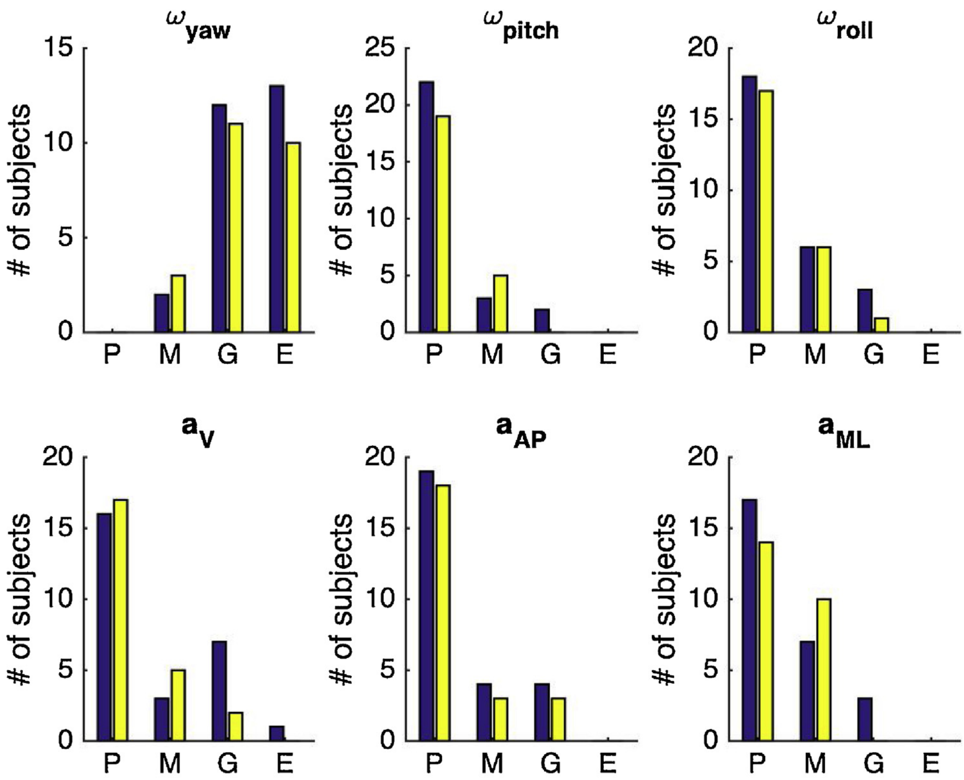

Fig. 1. The bar graphs of intra-subject reliability of turn acceleration and angular velocity signals. Yellow-PD, blue-CG. Abbreviations: P-poor, M-moderate, G-good, E-excellent.

Table 2
The true coverage probability of the bootstrap and Gaussian point-by-point methods (%). Abbreviations: CG = Control group; PD = Parkinson's disease patients.

		a_V	a_{ML}	a_{AP}	ω_{yaw}	ω_{pitch}	ω_{roll}
CG	Gauss	14	31	34	22	8	14
	Bootstrap	80	94	85	91	71	74
PD	Gauss	14	22	40	31	11	20
	Bootstrap	80	94	88	85	74	85

both groups. Vertical acceleration curves exhibit a full scale of reliabilities (from poor to excellent) in CG and slightly lower in PD (from poor to good). The reliability spreads from poor to good was observed for medio-lateral and antero-posterior acceleration, in both groups. For details refer Fig. 1.

3.3. Prediction bands

The width of the bootstrap PBs for all kinematic parameters was larger than the point-by-point Gaussian PB width (Figs. 2–3).

The results of the cross-validation calculations were as follows. For bootstrap PB in CG, the estimated true achieved coverage ranged from 80% to 94% for acceleration curves and from 71% to 91% for angular velocities. In PD, the reached coverage spread from 80% to 94% for acceleration and 74% to 75% for angular velocities (Table 2).

The estimated true achieved coverage for PB constructed from point-by-point PB was significantly lower than the coverage from the bootstrap method in all tested cases (maximum coverage was 40%, Table 2).

3.4. Groups comparison

The Cohen's d showed short sections with large effect size in almost all analyzed cases (i.e., ω_{yaw}, ω_{pitch}, a_V, a_{ML}, a_{AP}). The ω_{yaw} demonstrated the highest proportion of differences with medium effect size. The a_V and a_{ML} revealed the highest proportion of very small effect size (Fig. 4).

4. Discussion

The current study employed statistical methods to analyse walking turn curves from an instrumented Timed-Up and Go test. Using intra-class correlation this study provides assessment of within-group common patterns and intra-subject repeatability of turn angular velocity and acceleration. Next, the range of the likelihood of the turn kinematics of the subject group was determined via prediction bands. Additionally, this study provides a unique comparison of turning curves from different subject groups: healthy subjects and PD patients.

Four fundamental questions have been analysed. First, our findings showed that yaw angular velocity has the most repeatable curve pattern within both examined subject groups, PD and CG. Other curves exhibited low reliability for the curve pattern indicating that no true curve characteristic for the subject groups exists.

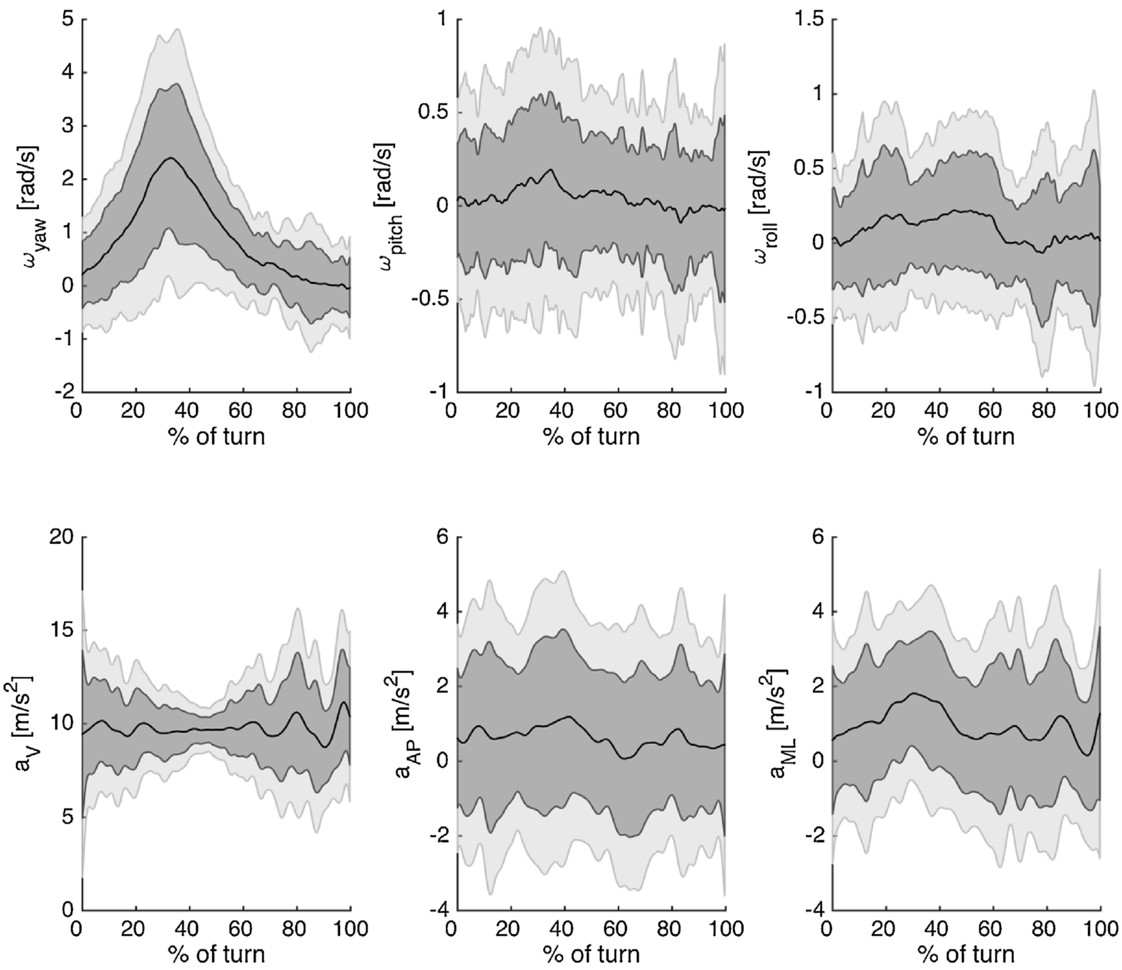

Fig. 2. Kinematic data of the trunk over the entire turning cycle of PD along with estimated prediction bands. Light gray-bootstrap method, dark gray-Gaussian point-by-point, black line-groups mean.

Therefore, these curves do not seem to be suitable for application of continuous analysis, e.g., analysis of the curve shape. However, it does not generally imply that these curves are not suitable for turn analysis at all. After careful selection, these curves can serve as a basis for discrete parameters calculation.

Second, the intra-subject reliability refers to the agreement of two or more curves from the same subject. The highest reliability was demonstrated by the yaw angular velocity in both subject groups.

It was pointed out, that the adoption of movement analysis in a clinical practice requires reliable data [24]. With regard to this statement and based on the reliability results presented and discussed above (intra- and inter- subjects) we consider the yaw angular velocity curve as the most suitable for turn manoeuvre analysis and for application in clinical practice. However, the lower reliability, i.e. higher variability, should be a subject for further research and investigation [25].

Third, when comparing prediction bands for turning curves using bootstrap and Gaussian point-by-point methods, this study revealed a significantly lower coverage when using Gaussian point-by-point method. This is in line with previous studies analysing the prediction bands of lower limbs angles of gait [8], turn [18], and kinematics of the cervical spine [11]. Although the acceleration curves exhibited high coverage by the bootstrap method, large prediction bands' width was observed (Figs. 2 and 3) which indicates the presence of high inter-subjects' variability along the entire turn curves. This corresponds to findings that a common curve pattern is missing (see above). Based on this, we can deduce that these curves are not eligible for deciding whether the subject's curve belongs to a specific subject group or not.

Fourth, the inter-group comparison built on the comparison of the group mean curves indicated that the yaw angular velocity has a great potential to distinguish between PD and the CG and will be the subject of ongoing analysis.

There are some potential limitations that need to be mentioned. A major limitation of this study is that number of participating men and women were not equal. Although there is evidence for different gender related trunk roll sway in the gait of age matched older adults [26], we do not suppose that gender differences would affect the repeatability of turning manoeuvres.

In conclusion, we can recommend yaw angular velocity signal as the most appropriate signal for walking turn analyses.

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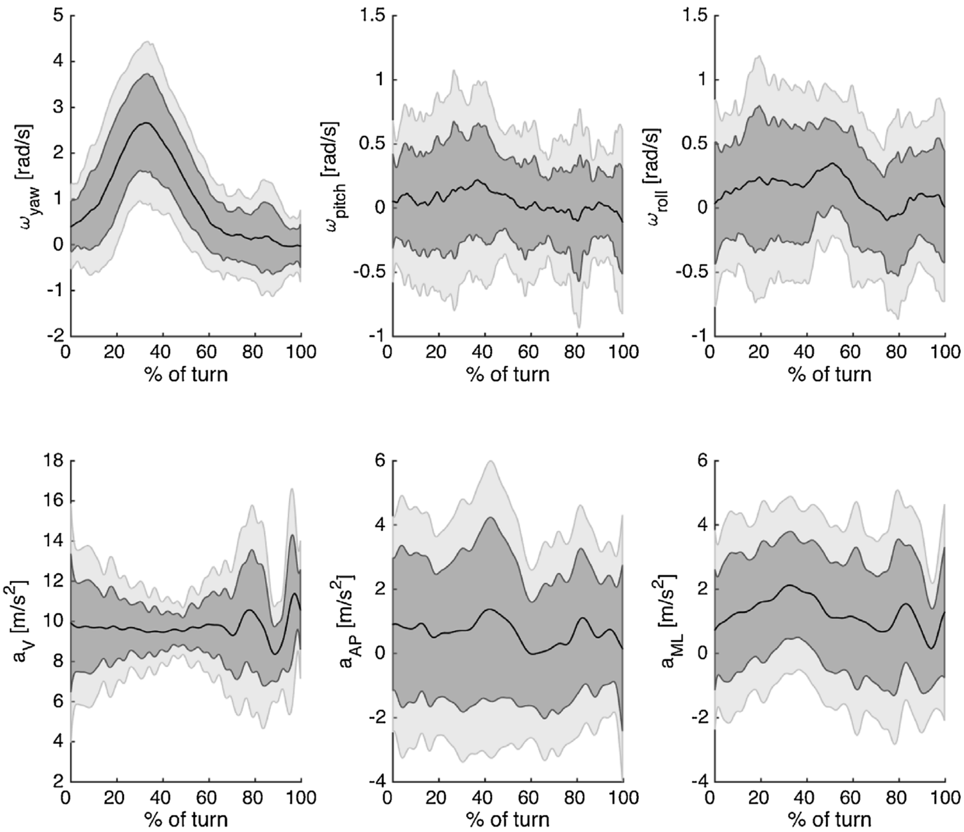

Fig. 3. Kinematic data of the trunk over the entire turning cycle of CG along with estimated prediction bands. Light gray-bootstrap method, dark gray-Gaussian point-by-point, black line-groups mean.

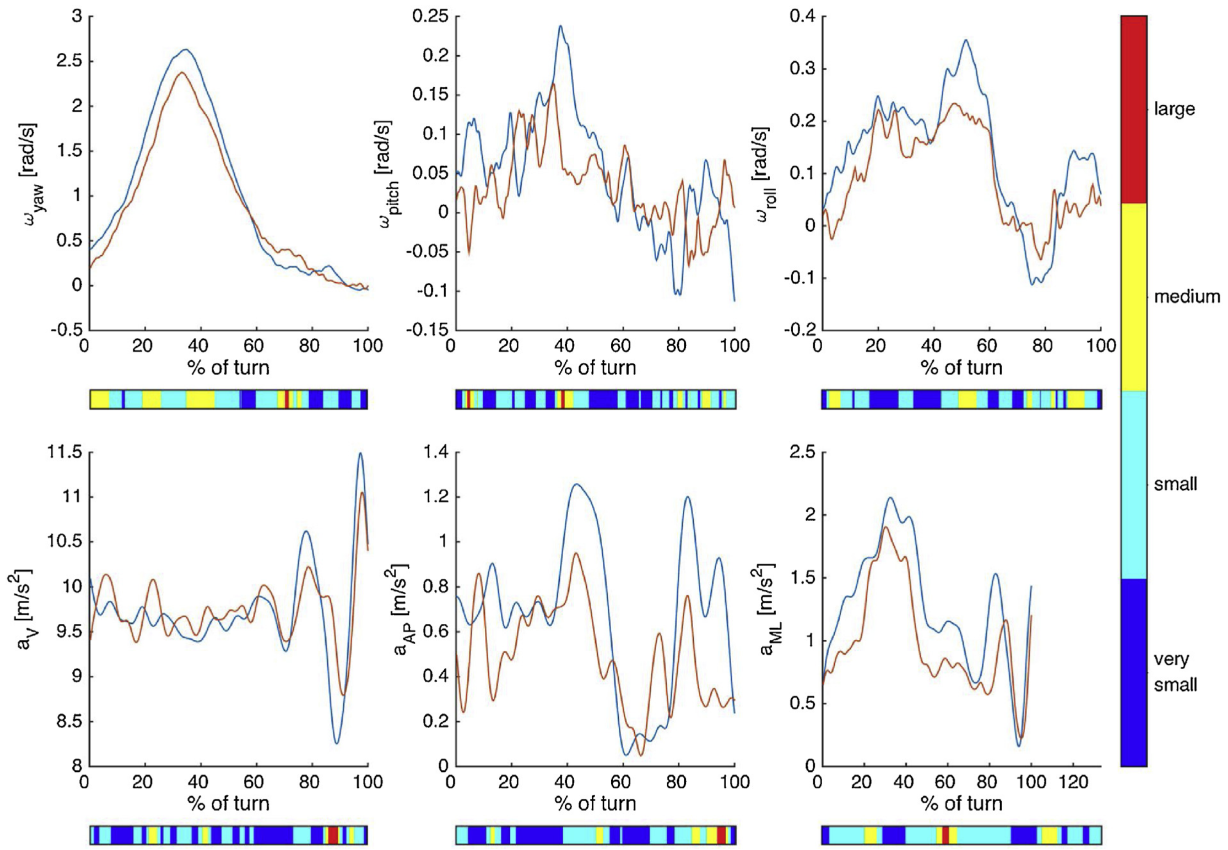

Fig. 4. Group's mean kinematic data of the trunk over the entire turning cycle. Colour bars show areas where the mean difference PBs revealed significant differences with intensity representing effect size of the differences varying from very small to large. Orange solid line - PD, blue solid line - CG.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] R.L. Wright, D.M. Peters, P.D. Robinson, A.J. Sitch, T.N. Watt, M.A. Hollands, Differences in axial segment reorientation during standing turns predict multiple falls in older adults, Gait Posture 36 (2012) 541–545, http://dx.doi.org/10.1016/j.gaitpost.2012.05.013.

[2] A. Mirelman, A. Weiss, A.S. Buchman, D.A. Bennett, N. Giladi, J.M. Hausdorff, Association between performance on timed up and go subtasks and mild cognitive impairment: further insights into the links between cognitive and motor function, J. Am. Geriatr. Soc. 62 (2014) 673–678, http://dx.doi.org/10.1111/jgs.12734.

[3] T. Herman, A. Weiss, M. Brozgol, N. Giladi, J.M. Hausdorff, Identifying axial and cognitive correlates in patients with Parkinson's disease motor subtype using the instrumented Timed Up and Go, Exp. Brain Res. 232 (2014) 713–721, http://dx.doi.org/10.1007/s00221-013-3778-8.

[4] A. Weiss, A. Mirelman, A.S. Buchman, D.A. Bennett, J.M. Hausdorff, Using a body-fixed sensor to identify subclinical gait difficulties in older adults with IADL disability: maximizing the output of the timed up and go, PLoS One 8 (2013), http://dx.doi.org/10.1371/journal.pone.0068885.

[5] B.C. Glaister, G.C. Bernatz, G.K. Klute, M.S. Orendurff, Video task analysis of turning during activities of daily living, Gait Posture 25 (2007) 289–294, http://dx.doi.org/10.1016/j.gaitpost.2006.04.003.

[6] A. Sant'Anna, N. Wickström, A symbol-based approach to gait analysis from acceleration signals: identification and detection of gait events and a new measure of gait symmetry, IEEE Trans. Inf. Technol. Biomed. 14 (2010) 1180–1187, http://dx.doi.org/10.1109/TITB.2010.2047402.

[7] M.W. Lenhoff, T.J. Santner, J.C. Otis, M.G.E. Peterson, B.J. Williams, S.I. Backus, Bootstrap prediction and confidence bands: a superior statistical method for analysis of gait data, Gait Posture 9 (1999) 10–17, http://dx.doi.org/10.1016/S0966-6362(98)00043-5.

[8] A. Duhamel, J.L. Bourriez, P. Devos, P. Krystkowiak, A. Destée, P. Derambure, L. Defebvre, Statistical tools for clinical gait analysis, Gait Posture 20 (2004) 204–212, http://dx.doi.org/10.1016/j.gaitpost.2003.09.010.

[9] A. Delval, J. Salleron, J.-L. Bourriez, S. Bleuse, C. Moreau, P. Krystkowiak, L. Defebvre, P. Devos, A. Duhamel, Kinematic angular parameters in PD: reliability of joint angle curves and comparison with healthy subjects, Gait Posture 28 (2008) 495–501, http://dx.doi.org/10.1016/j.gaitpost.2008.03.003.

[10] V.C. Bacon-Shone, J. Bacon-Shone, Gait of normal Hong Kong Chinese children: the bootstrap approach, Hong Kong Physiother. J. 18 (2000) 21–25, http://dx.doi.org/10.1016/S1013-7025(09)70013-2.

[11] W.J. Anderst, Bootstrap prediction bands for cervical spine intervertebral kinematics during in vivo three-dimensional head movements, J. Biomech. 48 (2015) 1270–1276, http://dx.doi.org/10.1016/j.jbiomech.2015.02.054.

[12] A.G. Cutti, I. Parel, M. Raggi, E. Petracci, A. Pellegrini, A.P. Accardo, R. Sacchetti, G. Porcellini, Prediction bands and intervals for the scapulo-humeral coordination based on the Bootstrap and two Gaussian methods, J. Biomech. 47 (2014) 1035–1044, http://dx.doi.org/10.1016/j.jbiomech.2013.12.028.

[13] N.A. Zakaria, Y. Kuwae, T. Tamura, K. Minato, S. Kanaya, Quantitative analysis of fall risk using TUG test, Comput. Methods Biomech. Biomed. Engin. 18 (4) (2015) 426–437, http://dx.doi.org/10.1080/10255842.2013.805211.

[14] D. Vervoort, N. Vuillerme, N. Kosse, T. Hortobágyi, C.J.C. Lamoth, Multivariate analyses and classification of inertial sensor data to identify aging effects on the timed-Up-and-Go test, PLoS One 11 (2016), http://dx.doi.org/10.1371/journal.pone.0155984.

[15] J.M.T. Van Uem, S. Walgaard, E. Ainsworth, S.E. Hasmann, T. Heger, S. Nussbaum, M.A. Hobert, E.M. Micó-amigo, R.C. Van Lummel, D. Berg, W. Maetzler, Quantitative timed-up-and-go parameters in relation to cognitive parameters and health-related quality of life in mild-to-moderate Parkinson's disease, PLoS One 11 (2016), http://dx.doi.org/10.1371/journal.pone.0151997.

[16] G. Adusumilli, S. Lancia, V.A. Levasseur, V. Amblee, M. Orchard, J.M. Wagner, R.T. Naismith, Turning is an important marker of balance confidence and walking limitation in persons with multiple sclerosis, PLoS One 13 (2018) 1–10, http://dx.doi.org/10.1371/journal.pone.0198178.

[17] J.A. O'Keefe, E.E. Robertson, B. Ouyang, D. Carns, A. McAsey, Y. Liu, M. Swanson, B. Bernard, E. Berry-Kravis, D.A. Hall, Cognitive function impacts gait, functional mobility and falls in fragile X-associated tremor/ataxia syndrome, Gait Posture 66 (2018) 288–293, http://dx.doi.org/10.1016/j.gaitpost.2018.09.005.

[18] P.C. Dixon, J. Stebbins, T. Theologis, A.B. Zavatsky, Spatio-temporal parameters and lower-limb kinematics of turning gait in typically developing children, Gait Posture 38 (2013) 870–875, http://dx.doi.org/10.1016/j.gaitpost.2013.04.010.

[19] P.C. Dixon, J. Stebbins, T. Theologis, A.B. Zavatsky, Ground reaction forces and lower-limb joint kinetics of turning gait in typically developing children, J. Biomech. 47 (2014) 3726–3733, http://dx.doi.org/10.1016/j.jbiomech.2014.09.011.

[20] J. Wall, C. Bell, S. Campbell, J. Davis, The timed Get-up-and-Go test revisited: measurement of the component tasks, J. Rehabil. Res. Dev. 37 (2000) 109–113.

[21] A. Salarian, C. Zampieri, F.B. Horak, P. Carlson-Kuhta, J.G. Nutt, K. Aminian, Analyzing 180° turns using an inertial system reveals early signs of progress in Parkinson's disease, Conf. Proc. IEEE Eng. Med. Biol. Soc. 2009 (2009) 224–227, http://dx.doi.org/10.1109/IEMBS.2009.5333970.

[22] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, J. Chiropr. Med. 15 (2016) 155–163, http://dx.doi.org/10.1016/j.jcm.2016.02.012.

[23] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, 2nd ed., Routledge, 1988, p. 27.

[24] E. Smith, L. Walsh, J. Doyle, B. Greene, C. Blake, The reliability of the quantitative timed up and go test (QTUG) measured over five consecutive days under single and dual-task conditions in community dwelling older adults, Gait Posture 43 (2016) 239–244, http://dx.doi.org/10.1016/j.gaitpost.2015.10.004.

[25] R. Schniepp, M. Wuehr, C. Schlick, S. Huth, C. Pradhan, M. Dieterich, T. Brandt, K. Jahn, Increased gait variability is associated with the history of falls in patients with cerebellar ataxia, J. Neurol. 261 (2014) 213–223, http://dx.doi.org/10.1007/s00415-013-7189-3.

[26] S.W. Lee, J. Verghese, R. Holtzer, J.R. Mahoney, M. Oh-Park, Trunk sway during walking among older adults: norms and correlation with gait velocity, Gait Posture 40 (2014) 676–681, http://dx.doi.org/10.1016/j.gaitpost.2014.07.023.

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Waveform skewness: Parameter for timed Up & Go turn assessment

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ABSTRACT

Turning is an essential part of human movement. Turning manoeuvres are affected by age, neurological disorders, or frailty. Analyses of the walking turn and its alterations could provide valuable information about functional independence. Most studies involving wearable sensors quantify the turn by descriptive statistical values such as the mean or maximum of the signal. Along with growing interest in walking turn analysis, new parameters should be proposed. From statistics we adapted a parameter, referred to as waveform skewness, that describes the shape of the 180° turn signal. This parameter is then compared to established ones and an intraclass-correlation is calculated. The mutual relationship between the proposed parameter and established ones is investigated via correlation. In addition, the effect of different circumstances (temporal alignment, signal scaling and time shift) to the proposed parameter is quantified. Waveform skewness showed a moderate intra-class correlation and a high correlation with the signal peak value. The results showed that waveform skewness is not sensitive to the time shift but is sensitive to signal scaling and temporal alignment. Comparing the waveform skewness between the two subject groups revealed significant differences between Parkinson disease patients and the control group. Quantitative assessment of the 180° turn may allow for more objective and sensitive determinations of movement disorders and pathologies.

1. Introduction

Walking, turning, standing from a seated position and sitting down are commonly performed daily activities. Turning is a challenging and complex task. It requires planning, control and re-orientation of the effective body segments to safely change the direction of movement [1].

It has been shown that turn assessment can provide valuable information for determining safe ambulation and functional independence [2,3]. Recently, is has been observed that deficits in walking turns are exhibited by frail people [4], older adults [5], people with a higher risk of falling [6,7] or people with neurological disorders [8]. Age affects turning maneuvers [9] as well as walking velocity [10].

Although motion capture laboratories are powerful and widely used in walking turn analysis, these systems are expensive and require a large dedicated space. Progress in the development of wearable sensors and its attainability has enabled using an instrumented TUG test which involves inertial movement measuring units that makes quantitative turn assessment more suitable in a clinical context and has resulted in growing attention to turn research. Besides complex models [11] used to quantify turning behavior, raw information obtained by the sensor (i.e., acceleration and/or angular rate) has been widely employed. These studies have assessed the turn duration [5,12–19], step-based parameters (e.g., number of steps) [5,12,14,17,18], and statistical properties of the angular rates or acceleration (e.g. mean, max) [5,12,13,17–20]. However, these parameters are not capable of capturing the complex properties of the turn signal, such as how the signal changes over time.

The turn is a nonperiodic and nonsymmetrical movement. Therefore, conventional parameters widely used to evaluate cyclic and bilateral movements, such as symmetry or variability, are not appropriate in turn analysis. Further, the turn signal is considerably short, and is thus not suitable for use in novel analytical methods, for example, those based on nonlinear analysis.

This paper aims to introduce a coherent and meaningful parameter to quantify kinematic data for the 180° turn of a Timed Up & Go (TUG) test and compare its performance with the performance of

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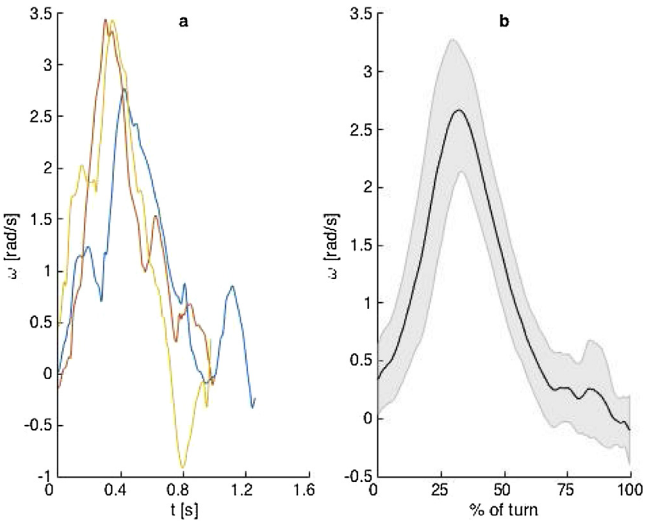

Fig. 1. Examples of angular rate about the yaw axis. a) Angular rate of the three subjects and b) the average signal of all the tested subjects (black line) and SD (gray area).

established parameters. The proposed parameter considers signal changes over the turn time.

2. Waveform skewness

We have developed a parameter termed as waveform skewness (WS) to provide quantitative metrics to describe and compare turn patterns. This approach is proposed to be used for evaluating the shape of the angular-rate time series. As the turn's angular rate about the yaw axis is bell shaped (Fig. 1), this technique is based on bell property assessment. Inspired by higher-order central moment in statistics; namely the third central moment, skewness; widely employed for the distribution function for assessing the shape of the data, we propose WS as a parameter for assessing a signals shape. The statistical skewness of a random variable $X=\{x_1, x_2, \ldots, x_n\}$ is computed as

$$S = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\mu)^3}{\left[\frac{1}{n}\sum_{i=1}^{n}(x_i-\mu)^2\right]^{3/2}}$$

and describes the asymmetry in a statistical distribution function, in which the curve appears distorted/skewed either to the left (positive number) or to the right (negative number). The proposed WS uses this characteristic for measuring the signal shape. The characteristics of the turn signal is like the skewed distribution function (Fig. 1), therefore it is possible to apply the calculation for statistical skewness to quantify the asymmetry of the turn. The turn signal can be seen as a virtual distribution function of a random variable. First, we can infer the random variable from the virtual distribution function. Then, we can calculate the statistical skewness of the inferred random variable which describes the shape (asymmetry) of the virtual distribution function. We refer to the results as the waveform skewness of the turn signal. The inference of waveform skewness is depicted on Fig. 2.

The analyzed angular velocity $\omega = (\omega_1, \ldots, \omega_n)$, where n is the signal length, presents for the WS computation a virtual statistical distribution (Fig. 2).

The total number of elements of the random variable, m, is calculated as the sum of the signal (i.e. virtual distribution) values:

$$m = \sum_{i=1}^{n}\omega_i$$

and the mean of random variable is calculated as:

$$\mu = \frac{\sum_{i=1}^{n}\omega_i t_i}{m}$$

where t is a unit-spaced vector with elements $[1, 2, \ldots, n]$.

Finally, the WS value of the signal is computed as

$$WS = \frac{\frac{1}{m}\sum_{i=1}^{n}(t_i-\mu)^3\omega_i}{\left[\frac{1}{m}\sum_{i=1}^{n}(t_i-\mu)^2\omega_i\right]^{3/2}}$$

WS characterizes the asymmetry of the turn. A positive value shows that the signal and the angular velocity increases faster at the beginning of the turn, whereas the negative number shows that the turn is performed faster at its conclusion.

3. Materials and methods

3.1. Subjects

The study was performed within the frame of a larger research protocol. We included 37 Parkinson disease patients (PD) (26 males, 11 females), mean age 58.6 (+−13.4) years and 36 older adult volunteers as a control group (CG) (33 males, 3 females), mean age 64.4 (+−9.5) years without any history or signs of balance problems or any neuropsychiatric disorders. An informed consent was obtained from each subject. The study was approved by the Ethics Committee of the General University Hospital in Prague, Czech Republic, and therefore performed in accordance with the ethical standards established in the 1964 Declaration of Helsinki.

3.2. Data acquisition

Kinematic data was recorded from three gyro-accelerometers (MTx units, Xsens Technologies B.V.) with a data sampling rate of 100 Hz. Gyro-accelerometer units were placed on the subject's body segments in compliance with a study done by Salarian et. al. [21]: two units were symmetrically attached to the lateral shank of each lower extremity 4 cm above the ankle joint, and a third unit was attached on the chest, 2 cm below the sternal notch. An extended version of the TUG (10 m walk) was used for the recordings. In the test, a participant got up from his/her chair, walked 10 m, turned at a designated spot, returned to the seat, and sat down. To assess intra-session reliability of the measurements, ten subjects in each group performed an additional three trials of the TUG.

3.3. Data processing

Before processing, the raw signal was filtered through a low-pass filter with a zero-phase second-order Butterworth filter with a cut-off frequency of 20 Hz. The TUG subcomponents, namely sit-to-stand, gait, turn, and turn-to-sit, were automatically identified. The identification methods of each TUG subcomponent is described

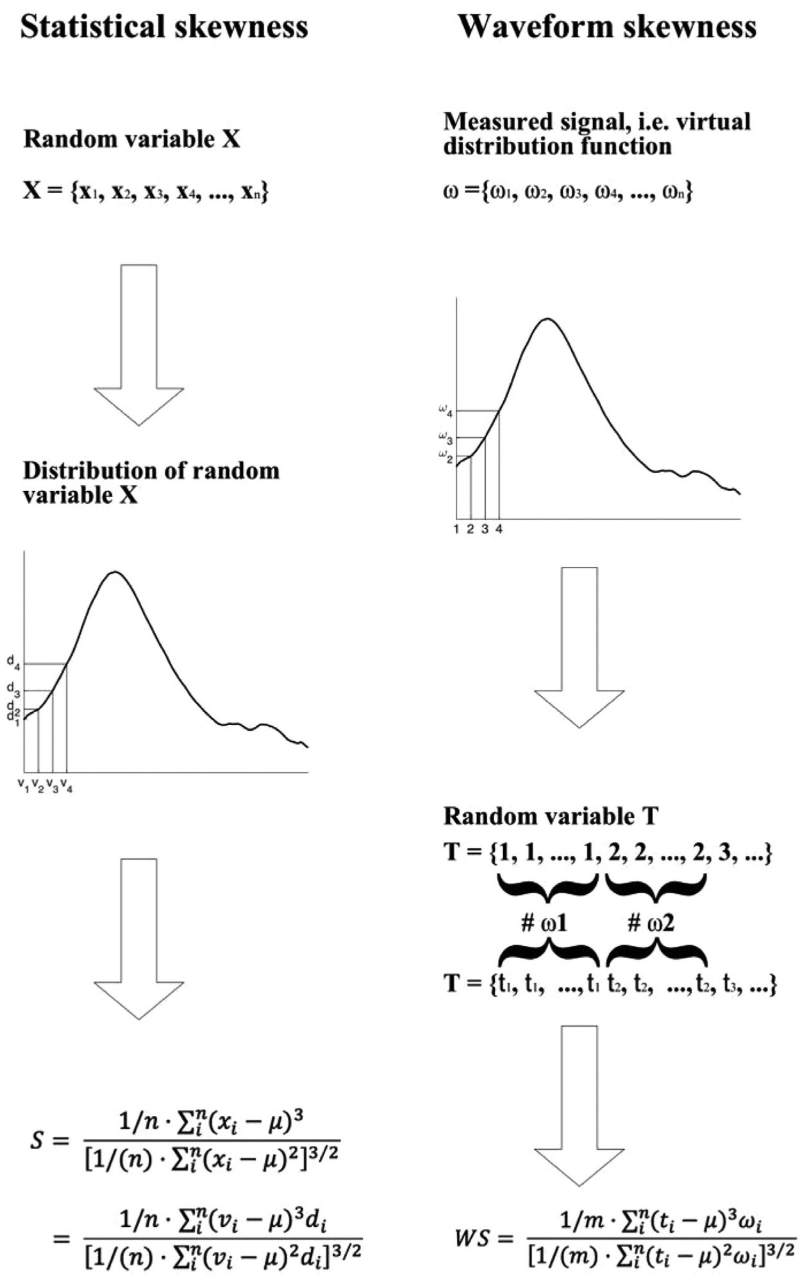

Fig. 2. Inference of waveform skewness from measured signal. Left: statistical skewness analogy. Right: waveform skewness inference.

in detail in [12]. Next, the turn angular rate, acquired through the chest sensor, was further processed. The turn parameters, namely duration, mean, peak value, and WS were then calculated.

Prior to the WS analysis, left and right turns needed to be differentiated. To waive the direction of rotation (left or right), the direction needed to be unified. A positive angular velocity indicates a clockwise rotation in the direction of the axis of rotation, while a negative angular velocity indicates a counter-clockwise rotation. Thus, signals with a negative integral value were inverted. Two options could be considered for achieving only positive values. The first was to use absolute values for the signal, thus achieving angular velocity without the use of direction information. The second option was to shift the signal $\omega = (\omega_1, \ldots, \omega_n)$ by its minimal value.

$$\omega_i = \omega_i + abs(\min(\omega)).$$

To do such, we preserved directional information, i.e., the threshold abs(min(signal)) differentiates between directions. We performed further analysis for the second option, i.e., shifted signals.

3.4. Parameter analysis

All parameters were tested under different circumstances. We focused on demonstrating the effect of signal scaling (Fig. 3a), temporal alignment (Fig. 3b), and time shifting (Fig. 3c) for the results of the parameters.

As the normalization of signal values to the same range is widely used in movement analysis, we investigated the effects of signal scaling on turn parameters. To demonstrate the effect of signal scaling, we separately multiplied and normalized the original signal.

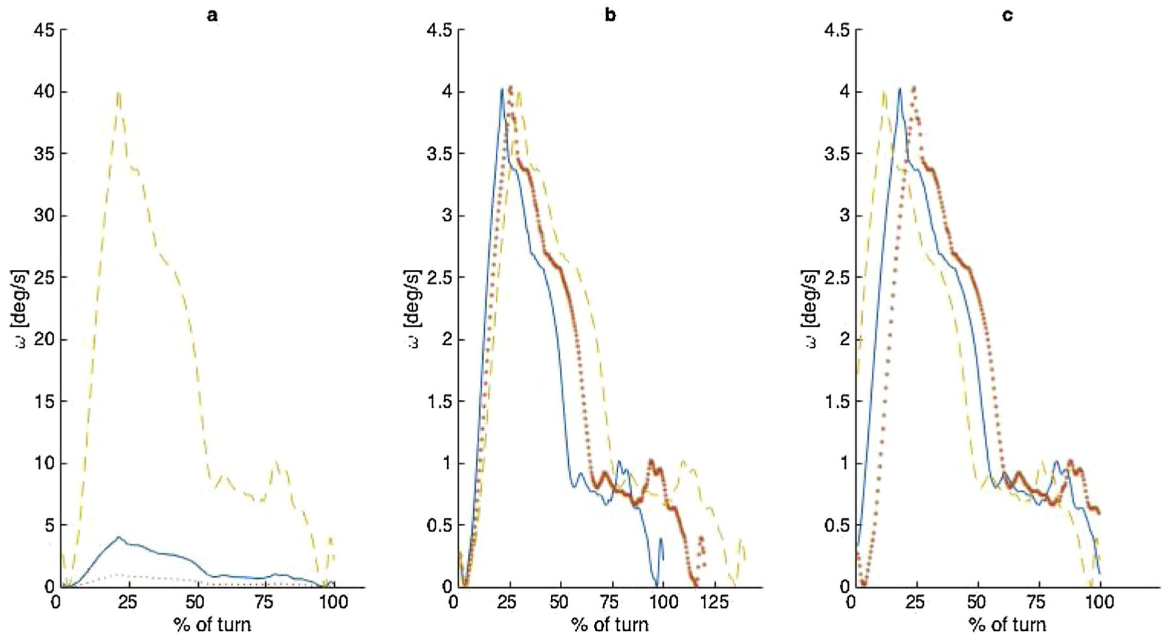

Fig. 3. Signal adjustments. a) Scaling of the signal: the solid line represents the original signal, dotted line represents the signal normalized to interval <0,1>, and dashed line represents the signal scaled to 10-times the original signal. b) Temporal alignment: the solid line represents the original signal, dotted line represents the signal interpolated to 120% of the original length, and dashed line represents the signal interpolated to 140% of the original length. c) Shifting of the signal: the solid line represents the original signal, dashed line represents the signal shifted toward the beginning of the turn, and dotted line represents the signal shifted away from the beginning of the turn.

The normalization of the signal to range (0,1) was performed as follows:

$$\Omega_i = \frac{\omega_i - min(\omega)}{max(\omega) - min(\omega)}$$

where ω and Ω were the analyzed and normalized angular rates, respectively.

As the temporal alignment of signals, i.e., signal interpolation to the same length, is used in movement analysis, we interpolated the turn signal to 120% and 140% of its original length.

The greatest difficulty in analyzing turns is in identifying the onset and offset of the turns [21]. Therefore, we simulated inaccurate turn detection with a signal shift. To demonstrate the effect of the time shift, we shifted the signal by approximately 15% of the turn duration toward and away from the initial position.

3.5. Statistical analysis

After calculating the parameter values of all subjects under different circumstances, the one-way ANOVA with repeated measures was used to compare the parameter results. The significance level was set to 0.05.

Also, the strength of the relationship between the computed parameters was analyzed. The relationship between parameters is described via the Pearson correlation coefficient. A correlation greater than 0.9 (lower than −0.9) was considered as very high, a correlation greater than 0.7 (less than −0.7) was reported as high, a correlation greater than 0.5 (less than −0.5) was moderate, a correlation greater than 0.3 (less than −0.3) was designated as low, and a correlation between 0.3 and -0.3 indicated a negligible relationship [22].

To evaluate the reliability of turn derived parameters, intraclass correlation (ICC) was used. Since the same subjects and same device were used for reliability, an ICC(1,1) was used for all parameters. An absolute agreement, ρ, and 95% confidence intervals was reported. A reliability greater than 0.90 was considered as excellent, a reliability greater than 0.75 was considered as good, greater than 0.50 was moderate, and lower than 0.50 was poor.

Table 1
The effects of various signal adjustments (scaling, temporal alignment, time shift) to the parameter results.

	Scaling	Interpolation	Time shift
Duration	1.00	1.00	**< 0.01**[*]
Mean	**< 0.01**[*]	**< 0.01**[*]	**< 0.01**[*]
Peak	**< 0.01**[*]	1.00	1.00
WS	0.95	0.99	**< 0.01**[*]

[*] Statistically significant differences.

All analysis algorithms, as well as statistical evaluation of the outcomes were carried out in a MATLAB environment (MatLab R2015b, Mathworks).

4. Results

4.1. Effect of different circumstances

The mean and peak showed a significant difference in the results for different signal scaling ($p < 0.01$). The WS parameter, duration and mean showed a statistically significant difference for different time shifts ($p < 0.01$). For details about results under various circumstances (adjustments) see Table 1.

4.2. Intraclass correlation

The turn duration, signal mean and peak values showed a good reliability ($\rho > 0.75$) for PD although moderate ($\rho > 0.50$) for the CG. The WS demonstrated a moderate reliability ($\rho > 0.50$) for both tested subject groups. Table 2 summarizes the reliability results.

4.3. Correlation of parameters

A third analysis compared turn parameters to each other. The WS had a moderately positive correlation ($r = 0.64$ and 0.59, respectively) to the mean and peak value for the CG although it had a low positive for PD. The WS correlation to duration was moderate neg-

Table 2
The reliability of the TUG turn parameters for the angular rate around the yaw axis. ρ = intraclass coefficient of correlation, LL = lower limit, UL = upper limit.

Parameter	CG			PD		
	ICC	95% CI bounds		ICC	95% CI bounds	
	ρ	LL	UL	ρ	LL	UL
Duration	0.55	0.38	0.79	0.85	0.74	0.92
Mean Angular Rate	0.60	0.53	0.81	0.83	0.71	0.91
Peak Angular Rate	0.68	0.35	0.86	0.77	0.61	0.87
WS	0.68	0.44	0.86	0.66	0.45	0.81

Table 3
Correlation of TUG-turn parameters for both subject groups.

	CG			PD		
	Mean	Peak	Duration	Mean	Peak	Duration
WS	0.64	0.59	−0.57	0.46	0.47	−0.37
Mean	–	0.90	−0.98	–	0.82	−0.90
Peak	–	–	−0.92	–	–	−0.80

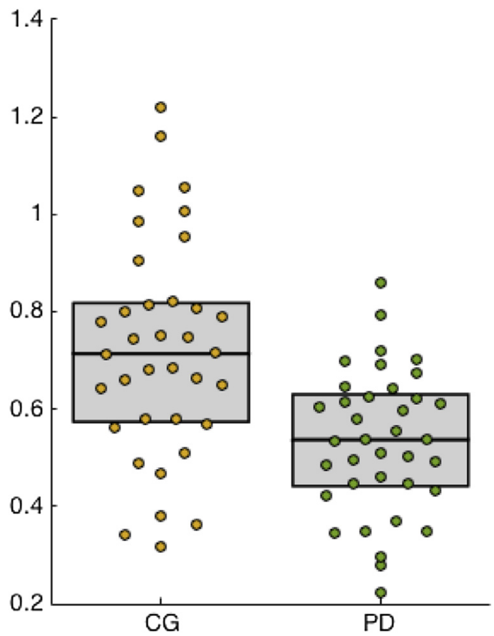

Fig. 4. Scatter plot of waveform skewness parameter for subject groups. CG – control group, PD – Parkinson disease patients.

ative (r=−0.57) for the CG and low negative (r=−0.37) for PD. The peak value had a moderate positive correlation to the WS (r = 0.59) for CG and low (r = 0.47) for PD. For other relationships, the correlation varied from high to very high. The results of correlation analysis for all parameters are shown in Table 3.

4.4. Subject group comparisons

The turn assessment via WS parameter revealed a significant difference between the CG and PD ($p < 0.001$), refer Fig. 4.

5. Discussion

The major contributions of this study are 1) the introduction of a parameter to quantify the turn component of the TUG, 2) a comparison of the proposed parameter to established parameters and clarification of its behaviour in different circumstances.

The proposed parameter, waveform skewness, is adapted from statistics and fitted to signal shape analysis. When comparing the reliability of the parameters for the CG to PD, the CG reliability was lower. Other studies [23,24] have shown similar trends, with the CG having lower ICCs when compared to PD. Waveform skewness reliability performance indicates that this parameter is sufficiently reliable for turn assessment. The moderate reliability may indicate that the waveform parameter reflects the natural individuality of the turn and the complexity of the signal. Nevertheless, waveform analysis may provide circumstantial insight into the changes of a movement pattern. Moreover, Mortanza [25] concluded that spatio-temporal analysis of level walking is not sufficient and cannot act as a reliable predictor for falls in elderly individuals. Waveform analysis of the TUG turn may lead to new findings and thus to improved insights and understanding of different pathologies.

The interpretation of the waveform skewness parameter is similar to its statistical counterpart.

The statistical skewness deals with asymmetry of the distribution of a random variable. In the case of turn angular rate, it indicates the angular rate distribution regardless the timing of the turn. In contrast, the proposed waveform skewness considers timing. Increasingly positive waveform skewness values indicate a higher angular rate at the beginning of the turn. Conversely, a negative value indicates a higher angular rate at the end of the turn. To our knowledge it is the first usage of skewness to signal shape assessment (not assessment of signal distribution).

When employing a parameter computation in the quantitative assessment of signal, an influence of specific characteristics of the signal on the calculation of parameter should be considered (e.g. the effect of signal normalization). Different parameters reflect various aspects of turn movement. Therefore, the selection of an appropriate parameter for a specified research aim is crucial in turn quantification.

Waveform skewness is subject to expected and reasonable responses to signal alteration. The parameter proved to be intact to signal scaling and signal temporal alignment, whereas it is sensitive to signal time shift (Table 1). Correlation analysis showed a moderate linear relationship between waveform skewness and peak value. As waveform skewness is intact to signal scaling, the peak correlation can be circumvented by signal normalization.

Testing the proposed parameter showed its ability to differentiate between subject groups. However, the ages and gender of the subject groups do not match perfectly. The age of the CG is higher than PD. It can be expected that in younger controls the difference compared to PD would have been even more pronounced. Regarding gender, to our knowledge, there is no evidence that gender affects turning behaviour.

Based on the presented results, we can gather that waveform skewness introduces a new point of view on TUG-turn quantification and has the potential to be used in this context. Moreover, this parameter is based on inertial measurement unit data, which includes a portable and low-cost sensor. As it is a prerequisite for ambulatory usage, it increases the usability of waveform skewness ouside this research area.

Since waveform skewness is not closely tied to the TUG turn, it can potentially be applied in the analysis of 180° turning under other circumstances. The approach for measuring waveform skewness presented here is only intended for trunk turn angular rate waveform and would not be appropriate for the assessment of discrete data derived from the turn. In addition, the approach should be only applied to the angular rate signal around the yaw axis, its application to other turn signals may not result in meaningful outcomes.

6. Conclusion

This study elucidated some of the properties of the four parameters for TUG turn assessment: three already established in turn analysis, one new parameter – waveform skewness – adapted from statistics and only proposed for turn analysis. Quantitative assessment of turning during the TUG may allow for more objective and sensitive determinations of movement disorders and pathologies. As the TUG is a widely used test in clinical settings, parameters that could be computed from its components (e.g. the turn) would be of enormous research and clinical benefit.

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Competing interests

None declared.

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References

[1] A.E. Patla, A. Adkin, T. Ballard, Online steering: coordination and control of body center of mass, head and body reorientation, Exp. Brain Res. 129 (1999) 629–634, http://dx.doi.org/10.1007/s002210050932.

[2] J.E. Harris, J.J. Eng, D.S. Marigold, C.D. Tokuno, C.L. Louis, Relationship of balance and mobility to fall incidence in people with chronic stroke, Phys. Ther. 85 (2005) 150–158, http://dx.doi.org/10.1093/ptj/85.2.150.

[3] L. Jørgensen, T. Engstad, B.K. Jacobsen, Higher incidence of falls in long-term stroke survivors than in population controls, Stroke 33 (2002) 542–547, http://dx.doi.org/10.1161/hs0202.102375.

[4] A. Galán-Mercant, A.I. Cuesta-Vargas, Differences in trunk accelerometry between frail and non-frail elderly persons in functional tasks, BMC Res. Notes (2014), http://dx.doi.org/10.1186/1756-0500-7-100.

[5] D. Vervoort, N. Vuillerme, N. Kosse, T. Hortobágyi, C.J.C. Lamoth, Multivariate analyses and classification of inertial sensor data to identify aging effects on the timed-Up-and-Go test, PLoS One 11 (2016), http://dx.doi.org/10.1371/journal.pone.0155984.

[6] F.B. Horak, M. Mancini, P. Carlson-Kuhta, J.G. Nutt, A. Salarian, Balance and gait represent independent domains of mobility in parkinson disease, Phys. Ther. 96 (2016) 1364–1371, http://dx.doi.org/10.2522/ptj.20150580.

[7] J.H. Ansai, L.P. de Andrade, T.H. Nakagawa, J.R. Rebelatto, Performances on the Timed Up and Go test and subtasks between fallers and non-fallers in older adults with cognitive impairment, Arq. Neuropsiquiatr. 76 (2018) 381–386 http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0004-282X2018000600381&nrm=iso.

[8] K. Lebel, C. Duval, H.P. Nguyen, R. Plamondon, P. Boissy, Cranio-Caudal kinematic turn signature assessed with inertial systems as a marker of mobility deficits in Parkinson's disease, Front. Neurol. 9 (2018), http://dx.doi.org/10.3389/fneur.2018.00022.

[9] C. Forsell, D. Conradsson, C. Paquette, E. Franzén, Reducing gait speed affects axial coordination of walking turns, Gait Posture 54 (2017) 71–75, http://dx.doi.org/10.1016/j.gaitpost.2017.02.020.

[10] D. Conradsson, C. Paquette, E. Franzén, Medio-lateral stability during walking turns in older adults, PLoS One 13 (2018), http://dx.doi.org/10.1371/journal.pone.0198455.

[11] K. Lebel, H. Nguyen, C. Duval, R. Plamondon, P. Boissy, Capturing the Cranio-Caudal signature of a turn with inertial measurement systems: methods, parameters robustness and reliability, Front. Bioeng. Biotechnol. 5 (2017) 51, http://dx.doi.org/10.3389/fbioe.2017.00051, 51-51.

[12] A. Salarian, F.B. Horak, C. Zampieri, P. Carlson-Kuhta, J.G. Nutt, K. Aminian, ITUG, a sensitive and reliable measure of mobility, IEEE Trans. Neural Syst. Rehabil. Eng. 18 (2010) 303–310, http://dx.doi.org/10.1109/TNSRE.2010.2047606.

[13] B.R. Greene, A. O'Donovan, R. Romero-Ortuno, L. Cogan, C.N. Scanaill, R.A. Kenny, Quantitative falls risk assessment using the timed Up and Go test, IEEE Trans. Biomed. Eng. 57 (2010) 2918–2926, http://dx.doi.org/10.1109/TBME.2010.2083659.

[14] C.D.C. de M. Faria, B. de Carvalho-Pinto, S. Nadeau, L.F. Teixeira-Salmela, 180° turn while walking: characterization and comparisons between subjects with and without stroke, J. Phys. Ther. Sci. 28 (2016) 2694–2699, http://dx.doi.org/10.1589/jpts.28.2694.

[15] J.M.T. Van Uem, S. Walgaard, E. Ainsworth, S.E. Hasmann, T. Heger, S. Nussbaum, M.A. Hobert, E.M. Micó-amigo, R.C. Van Lummel, D. Berg, W. Maetzler, Quantitative timed-Up-and-Go parameters in relation to cognitive parameters and health- related quality of life in mild-to-moderate Parkinson's disease, PLoS One 11 (2016), http://dx.doi.org/10.1371/journal.pone.0151997.

[16] S. Bovonsunthonchai, V. Hiengkaew, R. Vachalathiti, Temporospatial analysis: gait characteristics of young adults and the elderly in turning while walking, Int. J. Ther. Rehabil. 22 (2014) 129–134, http://dx.doi.org/10.12968/ijtr.2015.22.3.129.

[17] G. Adusumilli, S. Lancia, V.A. Levasseur, V. Amblee, M. Orchard, J.M. Wagner, R.T. Naismith, Turning is an important marker of balance confidence and walking limitation in persons with multiple sclerosis, PLoS One 13 (2018) 1–10, http://dx.doi.org/10.1371/journal.pone.0198178.

[18] J.A. O'Keefe, E.E. Robertson, B. Ouyang, D. Carns, A. McAsey, Y. Liu, M. Swanson, B. Bernard, E. Berry-Kravis, D.A. Hall, Cognitive function impacts gait, functional mobility and falls in fragile X-associated tremor/ataxia syndrome, Gait Posture 66 (2018) 288–293, http://dx.doi.org/10.1016/j.gaitpost.2018.09.005.

[19] M. Bertoli, A. Cereatti, U. Della Croce, M. Mancini, An objective assessment to investigate the impact of turning angle on freezing of gait in Parkinson's disease, 2017 IEEE Biomed. Circuits Syst. Conf. BioCAS 2017 – Proc. (2018) 1–4, http://dx.doi.org/10.1109/BIOCAS.2017.8325122.

[20] J. Silva, I. Sousa, Instrumented timed up and go: fall risk assessment based on inertial wearable sensors, 2016 IEEE Int. Symp. Med. Meas. Appl. (2016) 1–6, http://dx.doi.org/10.1109/MeMeA.2016.7533778.

[21] A. Salarian, C. Zampieri, F.B. Horak, P. Carlson-Kuhta, J.G. Nutt, K. Aminian, Analyzing 180° turns using an inertial system reveals early signs of progress in Parkinson's Disease, Conf. Proc. IEEE Eng. Med. Biol. Soc. 2009 (2009) 224–227, http://dx.doi.org/10.1109/IEMBS.2009.5333970.

[22] M.M. Mukaka, A guide to appropriate use of Correlation coefficient in medical research, Malawi Med. J. 24 (2012) 69–71 http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3576830/.

[23] M. Mancini, A. Salarian, P. Carlson-Kuhta, C. Zampieri, L. King, L. Chiari, F.B. Horak, ISway: a sensitive, valid and reliable measure of postural control, J. Neuroeng. Rehabil. 9 (2012) 59, http://dx.doi.org/10.1186/1743-0003-9-59.

[24] S. Viteckova, R. Krupicka, P. Kutilek, V. Cejka, Z. Szabo, M. Hoskovcova, E. Ruzicka, Wave kurtosis: a novel, specific parameter for TUG-turn quantification, IFMBE Proc. (2018) 339–343, http://dx.doi.org/10.1007/978-981-10-9038-7_64.

[25] N. Mortaza, N.A.A. Osman, M. Mehdikhani, Are the spatio-temporal parameters of gait capable of distinguishing a faller from a non-faller elderly? Eur. J. Phys. Rehabil. Med. 50 (2014) 677–691.

Příloha H

Cíl 7: Vlastní publikace

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Can a turn before sitting have additional value in parkinson disease assessment?

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1. Introduction

Turning before seating from a standing position is a commonly performed daily activity. The turning before sitting movement is an included part of functional tests such as the Timed Up&Go test (TUG). The increased utilization of wearable sensors increases the ability to separately evaluate individual TUG sub-tasks. A prolonged performance of transition sub-tasks (e.g. turn-to-sit) has been shown in Parkinson's disease (PD) patients [1,2]. However, analysis of the turn-before-sitting is not widely used. To our knowledge, there is no study dealing with a direct comparison of the source turn-before-sit signals. The main aim of this paper is to investigate whether an analysis of the turn-before-sit signals can provide additional value to an instrumented TUG performed by healthy adults and PD patients. To achieve this, we addressed the following partial-goals: (1) to visualize within group variability of the turn-before-sitting signals, and (2) to provide quantitative inter-group comparison of turn-before-sitting signals.

2. Research Question

Is there a difference in the turn-before-sitting tasks among PD patients and the control group (healthy adults)?

3. Methods

We included 24 mild treatment-naive Parkinson disease patients (15 males, 9 females), mean age 59.2 (SD 11.9) years in the study. The control group (CG) included 27 older healthy volunteers (24 males, 3 females), mean age 64.2 (SD 8.3) without a history of neurological disorders. All subjects performed an instrumented extended TUG wearing gyroscopes. The turn-before-sitting task was automatically extracted from each TUG measurement [1]. The angular velocity measured by the chest sensor was used for further processing. The visualization of signals within group variability was done via prediction bands (PB), the gaussian point-by-point method was utilized. The functional data analytic method HANOVA [3] was employed for inter-group comparison of the turn-before-sitting signals. The distinctive signal, yaw angular velocity, was evaluated.

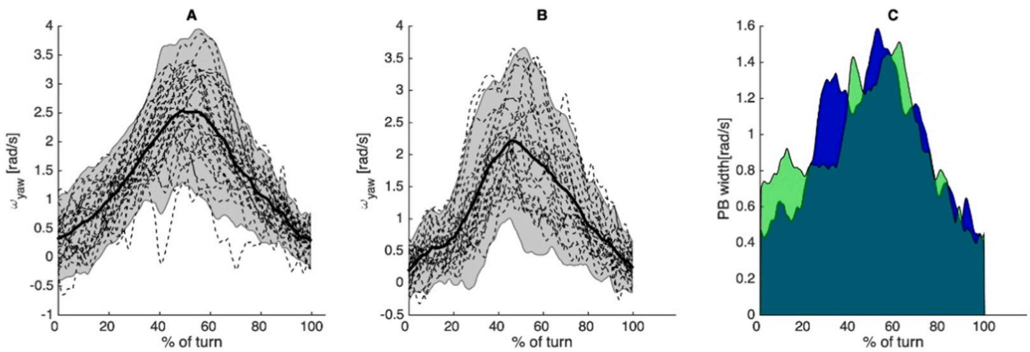

Fig. 1.

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4. Results

The gaussian point-by-point method showed a wider PB for the CG than for PD during the first 25 % of turn (Fig. 1C). Then the PB width of PD exceeded the width of the CG until circa half of the turn and finally the width of both groups were similar.

The HANOVA method revealed a statistically significant difference ($p = 0.004$) between the groups in the turn-before-sitting subtask.

5. Discussion

Our findings showed a difference in the turn-before-sitting movement between PD and CG. Which is in agreement with studies which focused on walking turn assessment [1] or the turn-to-sitting transition [1,2].

The width of the prediction bands indicated a higher movement variability in the CG in the first quarter of the turn while a higher variability in second quarter. The second half of the turn exhibited a similar variability in both groups.

In conclusion, the turn movement before sitting is suitable for further analysis of PD movement.

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References

[1] A. Salarian, F.B. Horak, C. Zampieri, P. Carlson-Kuhta, J.G. Nutt, K. Aminian, ITUG, a sensitive and reliable measure of mobility, IEEE Trans. Neural Syst. Rehabil. Eng. 18 (2010) 303–310, https://doi.org/10.1109/TNSRE.2010.2047606 .

[2] N.A. Zakaria, Y. Kuwae, T. Tamura, K. Minato, S. Kanaya, Quantitative analysis of fall risk using TUG test, Comput. Methods Biomech. Biomed. Engin. (2015), https://doi.org/10.1080/10255842.2013.805211 .

[3] T. Chau, S. Young, S. Redekop, Managing variability in the summary and comparison of gait data, J. Neuroeng. Rehabil. 2 (2005) 22, https://doi.org/10.1186/1743-0003-2-22 .