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Title: The validity of forceplate data as a measure of rapid and targeted volitional movements of the center of mass in transtibial prosthesis users

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Abbreviations: Limits of Stability (LoS), center of pressure (CoP), center of mass (CoM), transtibial prosthesis users (TPU), control-group (CON), tibialis anterior (TA), gastrocnemius medialis (GM), vastus lateralis (VL), biceps femoris (BF), erector spinae (ES), reaction time (RT), maximum excursion (MXE), mean velocity (MVL), directional control (DC), electromyography (EMG), median (M), interquartile range (IQR).

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Abstract

Purpose: To validate outcome variables from the Limits of Stability protocol that are derived from the center of pressure with those same variables derived from the center of mass during rapid, volitional responses in transtibial prosthesis users.

Method: Prosthesis users (n=21) and matched controls (n=21) executed movements while force and motion data were collected. Correlation coefficients were used to investigate relationships between center of pressure and center of mass for: x/y coordinates positions, Limits of Stability outcome variables and muscular reaction times.

Results: Significant differences were seen in correlation between x/y coordinate positions toward the intact limb (mean effect size of differences: $r = 0.38$). Limits of Stability variables were positively correlated (reaction time and maximum excursion range r_s : 0.585 – 0.846; directional control and mean velocity range r_s : 0.307 – 0.472). Muscular reaction times correlated weakly with those from center of pressure (mean r_s prosthesis users – 0.186 and controls – 0.101).

Conclusions: Forceplate measures are valid in describing rapid, volitional movements in unilateral transtibial prosthesis users. Limits of Stability outcomes extracted from center of pressure and center of mass are highly correlated but can be sensitive to direction. Muscular reaction time correlates very little with reaction times extracted from the other variables.

Introduction

The ability to stand and coordinate movements of the body are a basic requirement for physical function and execution of activities of daily living [1] and have a direct effect on quality of life [2]. Requirements for this ability are increasingly challenging when physical structures, which are integral in the coordination of movement, are removed. Such is the case for individuals who have undergone a limb amputation [3]. These individuals must coordinate whole-body movements despite the lack of critical structures, such as the foot, ankle, and more proximal joints. Balance confidence is also decreased in prosthesis users [4,5] and these individuals fall more frequently than age matched controls [6,7].

Volitional movement of the body in transtibial prosthesis users has been investigated in previous studies. When asked to lift one leg, prosthesis users showed an earlier muscle activation of the tensor-fascia-latae when compared to controls [8,9]. Aruin, et al. [10] asked individuals to catch a falling ball and showed that prosthesis users showed an increased magnitude of activity on the intact side of the body, indicating what the authors describe as a postural adaptation. Curtze, et al. [11] used kinematics to determine reaction time following a tether-release fall and showed shorter reaction times following the drop regardless of side, but that the reactions were greater when lead with the intact side. As the reaction time variable is calculated using varying methods in these previously stated studies, it is difficult to draw conclusions based on the sum of the studies. It is necessary to study the muscular reaction times in combination with the center of pressure (CoP) and center of mass (CoM) in order further understand the coordination of volitional movements.

An additional test of volitional movement is called the Limits of Stability (LoS) [12-15]. This test investigates a participants' ability to shift their center of mass towards 8 predetermined goals and evaluates how effectively they can coordinate these movements without falling.

In our previous investigation [16], results suggested transtibial prosthesis users utilize real-time vibratory feedback in a feedforward (anticipatory) postural control strategy during the LoS protocol. It has been shown that LoS outcome variables associated with accuracy and control improve in the 6 months following amputation but not the temporal variables [12]. Transtibial prosthesis users have reduced accuracy in movements directed backwards and towards the prosthesis and reduced limits towards the prosthetic side when compared to controls [15] and alignment changes do not affect these results [17].

Validity of the data derived from the LoS protocol rests upon the assumption that the variables derived from the center of pressure (CoP) are a reflection of the same variables derived from the center of mass (CoM). This is a result of the analytical model utilized in the analysis, referred to as the Inverted Pendulum Model [18,19]. This model dictates that the difference between the CoP and CoM (CoP-CoM) will be negatively correlated with the horizontal acceleration of the CoM. This model has been validated in for both able-bodied [18,19] and prosthesis users in quiet standing [20] but has been questioned when more dynamic activities are being conducted such as standing on an unstable platform [21] and walking [22,23]. To date, no studies have investigated specifically how movements of the CoP reflect those of the CoM during the inherently dynamic LoS protocol, or how the outcome variables from the LoS protocol based on the CoP reflect those from the CoM in prosthesis users. For this reason an exploratory study investigating the association of these variables is warranted.

The aims of this study are to: 1) validate the outcome variables of the LoS protocol in transtibial prosthesis users via CoP data, and movement of the CoM; 2) investigate the association between the reaction time as measured by movement of the CoP, CoM and that measured by EMG of the lower-extremity.

2 Methods

2.1 Participants

Data from a previous study investigating the use of vibratory feedback to improve postural stability was used [16] to conduct an a-priori sample size calculation. Utilizing differences and standard deviation of the reaction times towards the prosthesis with vibration and without vibration (174 ms [397]) it was determined that a total sample size of $n=42$ was required to detect a statistically significant difference ($p<0.05$) between two matched-groups, given a statistical power of 0.8, a minimum effect size of $d_z=0.44$.

An experimental group of transtibial prosthesis users (TPU; $n=21$) was recruited on the basis that they: had a unilateral transtibial amputation with no concomitant health issues, no current issues regarding fit or function of the prosthesis including wounds, blisters, or skin breakdown and had been a regular prosthesis user for at least one year. A control group (CON; $n=21$) was matched based on age, sex, height and weight. Participant characteristics are given in Table 1. All participants gave informed, written consent to the study which was approved by the Regional Ethical Review Board in Linköping, Sweden.

Participant	Sex	Height	Weight	Age	YSA	Cause	Control	Sex	Height	Weight	Age
1	M	182	82	63	18	Trauma	C1	M	177	76	62
2	M	173	94	67	24	Trauma	C2	M	172	103	65
3	M	181	66	30	13	Trauma	C3	M	185	68	32
4	M	178	84	43	17	Trauma	C4	M	185	86	47
5	M	181	60	60	21	Vascular	C5	M	177	66	60
6	F	170	70	51	33	Infection	C6	F	172	77	56
7	M	187	73	44	8	Trauma	C7	M	192	89	48
8	M	179	87	51	8	Trauma	C8	M	183	85	50
9	M	176	92	80	10	Trauma	C9	M	175	77	75
10	F	167	65	39	30	Trauma	C10	F	168	70	39
11	M	182	72	48	6	Trauma	C11	M	177	74	52
12	M	183	81	67	7	Trauma	C12	M	176	87	66
13	M	183	78	33	7	Trauma	C13	M	178	85	35
14	M	172	78	64	11	Vascular	C14	M	172	80	64
15	M	187	83	56	9	Vascular	C15	M	180	80	51
16	F	156	62	63	37	Trauma	C16	F	153	61	63
17	M	177	79	49	18	Trauma	C17	M	191	99	43
18	M	170	85	40	18	Trauma	C18	M	171	76	37
19	F	182	60	34	11	Infection	C19	F	166	59	33
20	M	173	100	50	4	Trauma	C20	M	180	96	42
21	M	180	100	29	7	Trauma	C21	M	185	107	38
<i>mean(SD) M=17;F=4 177.1(7.4) 78.6(12.2) 50.5(13.9) 15.1(9.4)</i>							<i>176.9(8.8) 81.0(13.0) 50.4(12.6)</i>				

Table 1 - Participant characteristics. Participants 1-21 from TPU with matched CON. Sex (M=male, F=female), Height (m), Weight (kg), Age (years), YSA=years since amputation (years), cause of amputation. Summary statistics (means and standard deviation (SD)) presented where appropriate.

2.2 Experimental Protocol

Prior to testing, the participants were fitted with a safety-harness in case of a fall. Surface EMG Trigno electrodes (Delsys Inc., Natick, USA) were positioned on lower-extremity musculature over the tibialis anterior (TA) and gastrocnemius medialis (GM) muscles on the non-amputated limb, and bilaterally on vastus lateralis (VL) and biceps femoris (BF), and the left and right erector spinae muscles (ES). Sixty-nine passive-reflective markers were placed to identify anatomical joints/segments of upper and lower-extremities. Markers were placed bilaterally at the medial and lateral malleolus, medial and lateral femoral condyles, greater trochanter, iliac crest, acromion, medial and lateral epicondyles and styloid processes. Foot segments were identified using 3 markers at the 1st metatarsalphalangeal joints, the 5th metatarsalphalangeal joints and the heel. The pelvis was identified using markers at the ASISs and sacrum. The head was identified using 3 markers placed medially, laterally and anteriorly. 9 additional segments were identified using marker clusters attached to the upper and lower arms and legs, and trunk. Using these reflective markers, CoM position was calculated for each individual based on anthropometric data [24] within the Visual 3D analysis software.

During testing participants stood on a forceplate (Pro Balance Master, NeuroCom International Inc., Oregon, USA). The system incorporates a 46 cm × 46 cm forceplate which is capable of sagittal plane pitch rotations in toes-up and toes-down directions. Participants stood on the forceplate facing a computer screen which prompted them through the LoS protocol. This test is an evaluation of the participant's ability to voluntarily shift CoM towards goals which represent their maximum distance from a central position in 8 directions (Fig. 1).

Fig. 1 – The eight (8) goal directions in the LoS protocol. Zero represents the starting point for all trials, and each goal direction following the cue to move. For the TPU, 2-4 are always towards the intact side and 6-8 towards the prosthetic side.

For each participant, it was first explained that the LoS protocol evaluated their ability to move their body as “quickly, straight and as far as possible” towards each of the 8 goals following the cue to move. Each test is 8 seconds in length following the cue to move. Participants were then given 3-5 practice tests in varying directions followed by a complete round of 8 tests under the normal test conditions. Following these practice tests one round of 8 tests was conducted according to the LoS protocol and subsequently used in the analysis. An 8-camera Oqus motion analysis system (Qualysis AB; Gothenburg, Sweden) captured full-body kinematics. Coordinate and EMG data were sampled at 100Hz and 1000Hz respectively using Qualisys Track Manager (QTM) (Qualysis AB; Gothenburg, Sweden). Force data was sampled at 100Hz within the embedded software in the Pro Balance Master (NeuroCom International Inc., Oregon, USA). An analog signal (5V rising) from the Pro Balance Master allowed synchronization of data from QTM and Pro Balance Master. All data was then exported to Visual 3D (C-Motion, Inc.; Germantown, USA) for processing.

2.3 Data Analysis

The coordinate system utilized defined all instances in the x-direction, y-direction and z-direction as mediolateral (*ML*; side-to-side), anteroposterior (*AP*; front-to-back) and inferosuperior (up-and-down) directions respectively. Outcome variables utilized in the analysis can be categorized into those associated with: 1) the CoP; 2) the CoM; and 3) EMG.

Center of Pressure

CoP data was derived using signals from four force transducers placed at the corners of 46 x 46 cm forceplate: (RF) right-front, (RR) right-rear, (LF) left-front and (LR) left-rear.

Calculations are based on equations 1 and

2:

$$CoP_x = \frac{(RF+RR)-(LF+LR)}{RF+RR+LF+LR} \times 10.2 \quad (1)$$

$$CoP_y = \frac{(RF + LF) - (LR + RR)}{RF + RR + LF + LR} \times 10.2 \quad (2)$$

Where RF, RR, LF, LR represent the instantaneous force at each transducer [25,26].

The dependent variables of interest were the reaction time (RT_{CoP}) (sec), Mean Velocity (MVL_{CoP}) (degrees/sec), Maximum Excursion (MXE_{CoP}) (degrees) and Directional Control (DC_{CoP}) (% of straight line). These variables have been described elsewhere [15,17,25] and are based on what is defined as the sway-angle (the angle formed by vertical projection of the center of the forceplate and a line projected through the individual's theoretical CoM). The ML- and AP-coordinate positions of the CoP (CoP_{ML} and CoP_{AP}) were also calculated for each of the 8-second tests (m). Normalization of goal directions for the TPU was conducted resulting in goals 2-4 being towards the intact side and 6-8 being towards the prosthesis for all trials (Fig. 1).

Center of Mass

Similar to those variables extracted from the CoP, dependent variables based on CoM [24] were reaction time (RT_{CoM}), Mean Velocity (MVL_{CoM}), Maximum Excursion (MXE_{CoM}) and Directional Control (DC_{CoM}). These variables were calculated based on the descriptions of the variables for the CoP [25] but using the ML- and AP-coordinate position of the CoM

instead of the CoP. The CoP variables are derived and modeled after movement of the theoretical angular movement of the CoM [25]. In contrast, these variables were derived using position and movement of the CoM. At the start of each trial a vertical projection of the CoM on the forceplate served as the adjacent side of a triangle formed between this and a hypotenuse from the point projected on the support surface and the CoM. In this way a “sway-angle” was formed using the CoM data and not the CoP.

For the calculation of each of the variables it was necessary to construct individual coordinate systems for each of the goal directions. In all directions the z-direction was defined by the starting point for each trial. Vertical from this point (based on the lab-coordinate system) was defined as the z-direction. The ML-direction was defined as a line bisecting the “zero” point of each trial (Fig. 1) and the goal for each trial. The AP-direction was defined as the perpendicular projection from the ML-direction. The z-direction was perpendicular to both the ML- and AP- directions (vertical). For analysis only the ML- and AP-directions were exported.

RT_{CoM} was defined as the length of time for the CoM to move through a sway-angle towards to the goal greater than 3SDs of the RMS-sway in the x-z plane (sagittal plane) during the 2 seconds prior to the cue to move (sec).

MXE_{CoM} was defined as the largest angle formed after the cue to move in the direction of the goal (x-z plane) (m).

MVL_{CoM} was defined as the total angular distance towards the goal (x-z plane) divided by the length of the trial (degrees/sec).

DCL_{CoM} was defined as the ratio of the total angular distance towards the goal (x-z plane) and the total angular distance not towards the goal (y-z plane) (%).

The x- and y-coordinate positions of the CoM (CoM_{ML} and CoM_{AP}) were also calculated for each of the 8-second tests (m).

EMG

The outcome variable for the EMG data was reaction time (RT_{EMG}) and was calculated for each of the individual muscle groups (TA, GM, VL, BF, ES). Reaction time was determined by calculating the RMS activity of each muscle group during the 100ms prior to the cue to move. RT was determined as the first instance the EMG signal deviated more the 3SDs from the RMS background activity (sec). For the purposes of analysis, left side CON muscles were compared to the intact of the TPU and right side CON compared to the affected side of the TPU.

Correlation coefficients (r_s) were calculated for each 8 second test using:

- 1) ML- and AP-coordinate positions of the CoP and CoM.
- 2) outcome variables (RT, MVL, MXE, DCL) derived from the CoP and CoM.
- 3) EMG reaction times (RT_{EMG}) and the RTs derived from the CoP and CoM.

2.4 Statistical Analysis

Normality of the data was determined using a Shapiro-Wilk test. In instances where normality was not shown non-parametric analyses were conducted. Statistical significance was determined using a critical alpha level of $\alpha=0.05$ for all tests.

In the ML- and AP-coordinate position of the CoP and CoM analysis descriptive data is presented with median and IQR. A Mann-Whitney-U test for independent samples was conducted to establish if significant differences existed between the ML- and AP-direction correlation coefficients between TPU and CON.

In the outcome variables analyses (RT, MVL, MXE, DC) of CoP and CoM descriptive statistics are provided for the within-group analyses. Statistical exploratory analysis utilized correlation coefficients (r_s) for the comparison of CoP and CoM variables to explore the association between the variables for each of 8 the directions.

The association between the EMG reaction times and the RT_{CoP} and RT_{CoM} was further explored using the descriptive statistics and correlation coefficients (r_s).

3 Results

2.2 CoP and CoM of the ML- and AP-coordinate positions

Statistically significant differences were seen between the TPU and CON when comparing the correlation coefficients for the ML- and AP-coordinate positions of the CoP and CoM. Differences (Median(IQR)) seen between the TPU and CON were towards the intact foot with goals 2_{AP} (TPU and CON; 0.97 (0.03), 0.95 (0.05), $p=0.011$), 3_{ML} (TPU and CON; 0.98(0.01), 0.97(0.03), $p=0.024$), and 3_{AP} (TPU and CON; 0.86(0.19), 0.61(0.52), $p=0.011$). Summary statistics given in Table 2.

Group		1 _{ML}	1 _{AP}	2 _{ML}	2 _{AP}	3 _{ML}	3 _{AP}	4 _{ML}	4 _{AP}	5 _{ML}	5 _{AP}	6 _{ML}	6 _{AP}	7 _{ML}	7 _{AP}	8 _{ML}	8 _{AP}
TPU	Median	0.90	0.97	0.98	0.97	0.98	0.86	0.98	0.96	0.91	0.94	0.96	0.94	0.98	0.86	0.98	0.96
	IQR	0.06	0.03	0.02	0.03	0.01	0.19	0.02	0.03	0.10	0.09	0.03	0.05	0.01	0.13	0.03	0.04
CON	Median	0.87	0.97	0.96	0.95	0.97	0.61	0.98	0.94	0.91	0.94	0.96	0.95	0.97	0.90	0.97	0.95
	IQR	0.20	0.02	0.03	0.05	0.03	0.52	0.01	0.06	0.07	0.05	0.03	0.05	0.03	0.13	0.03	0.04
p-value		0.589	0.372	0.058	0.011	0.024	0.011	0.473	0.252	0.521	0.642	0.505	0.263	0.204	0.660	0.870	0.660

Table 1 - Median and interquartile range (IQR) for the ML- and AP-direction correlation coefficient (r_s) of the CoP and CoM for the two groups (TPU & CON) for each of the goal directions (1-8). Goal directions normalized according to Figure 1, there 1=anterior, 2=anterior/intact, 3=intact, 4=posterior/intact, 5=posterior, 6=posterior/prosthesis, 7=prosthesis, 8=anterior/prosthesis. Bold text indicates statistically significant differences between TPU and CON.

3.2 Outcome variables (RT, MVL, MXE, DCL) derived from the CoP and CoM

Descriptive statistics were utilized to investigate the patterns of correlation between the CoP and CoM variables for the two groups. Results show that the strongest statistically significant positive correlations existed for both the TPU and CON within the RT (r_s – TPU: 0.591, $p=0.000$; CON: 0.663, $p=0.000$) and MXE (r_s – TPU: 0.846, $p=0.000$; CON: 0.585, $p=0.000$) variables. There were weak to moderate statistically significant positive correlations for both the TPU and CON within the DCL (r_s – TPU: 0.472, $p=0.000$; CON: 0.307, $p=0.000$) and MVL

(r_s – TPU: 0.432, $p=0.000$; CON: 0.351, $p=0.000$) variables. Summary statistics given in Table

3.

Group			DCL	RT	MXE	MVL
TPU	CoM	<i>M</i>	88,1	0,55	74,7	1,4
		<i>IQR</i>	15,7	0,17	20,4	1,3
	CoP	<i>M</i>	79,0	0,54	69,0	3,9
		<i>IQR</i>	17,5	0,23	21,0	2,5
	r_s		0,472	0,591	0,846	0,432
	<i>p-value</i>		,000	,000	,000	,000
CON	CoM	<i>M</i>	91,7	0,55	90,0	1,8
		<i>IQR</i>	13,3	0,14	22,8	1,5
	CoP	<i>M</i>	82,0	0,51	80,0	5,3
		<i>IQR</i>	11,0	0,18	13,0	3,4
	r_s		0,307	0,663	0,585	0,351
	<i>p-value</i>		,000	,000	,000	,000

Table 2 - Group median (*M*) and interquartile range (*IQR*) for each of the variables: directional control (DCL), reaction time (RT), maximum excursion (MXE), and mean velocity (MVL). Spearman correlation coefficient (r_s) provided with *p-value* for the within-group correlation analyses for both groups (TPU and CON): $DCL_{CoM}-DCL_{CoP}$, $RT_{CoM}-RT_{CoP}$, $MXE_{CoM}-MXE_{CoP}$, $MVL_{CoM}-MVL_{CoP}$.

Strong statistically significant positive correlations were seen for all directions in the MXE variable for both the TPU and CON. Similarly, strong statistically significant positive correlations were seen for most directions in the RT variable for both the TPU and CON with the exception of forward and backward (goal 1 and 5) for the TPU (r_s – 1: 0.419, $p=0.059$; 5: 0.419, $p=0.059$). Both the DCL and MVL variables exhibited varying levels of correlation with sporadic statistically significant differences being seen. Summary statistics given in Table 4.

Variable	Group	1		2		3		4		5		6		7		8		
		CoM	CoP	CoM	CoP	CoM	CoP	CoM	CoP	CoM	CoP	CoM	CoP	CoM	CoP	CoM	CoP	
DCL	TPU	M	87,8	79,0	88,4	86,0	94,1	84,0	85,3	72,0	82,2	74,0	77,1	63,0	90,9	85,0	89,9	77,0
		IQR	12,9	16,0	13,5	8,0	6,3	10,0	19,3	10,0	28,0	22,5	34,0	29,0	14,2	11,0	13,3	15,5
		r _s		0,052		-0,034		0,699		0,592		0,052		-0,034		0,699		0,592
		p-value		0,823		0,884		0,000		0,005		0,823		0,884		0,000		0,005
	CON	M	88,2	90,0	94,2	81,0	91,6	88,0	88,7	77,0	81,9	80,0	81,0	75,0	93,3	88,0	96,7	82,5
IQR		11,7	10,5	16,1	13,5	7,8	6,5	18,3	12,5	20,1	10,0	24,4	14,0	4,5	7,0	9,7	11,0	
r _s			0,326		0,261		0,404		-0,086		0,326		0,261		0,404		-0,086	
p-value			0,149		0,253		0,069		0,711		0,149		0,253		0,069		0,711	
RT	TPU	M	0,55	0,57	0,56	0,55	0,55	0,55	0,55	0,52	0,48	0,51	0,50	0,49	0,58	0,58	0,56	0,54
		IQR	0,20	0,60	0,14	0,22	0,19	0,46	0,15	0,19	0,20	0,21	0,25	0,30	0,20	0,27	0,18	0,21
		r _s		0,419		0,812		0,620		0,813		0,419		0,812		0,620		0,813
		p-value		0,059		0,000		0,003		0,000		0,059		0,000		0,003		0,000
	CON	M	0,57	0,55	0,52	0,46	0,54	0,50	0,58	0,55	0,53	0,49	0,58	0,50	0,56	0,52	0,56	0,51
IQR		0,14	0,23	0,17	0,22	0,15	0,16	0,17	0,27	0,19	0,22	0,15	0,13	0,15	0,18	0,11	0,20	
r _s			0,452		0,644		0,509		0,878		0,452		0,644		0,509		0,878	
p-value			0,040		0,002		0,018		0,000		0,040		0,002		0,018		0,000	
MXE	TPU	M	57,3	63,0	89,3	76,0	80,6	73,0	72,9	73,0	66,6	55,0	69,9	68,0	81,2	71,0	73,5	61,0
		IQR	20,9	15,5	21,3	17,5	12,2	15,0	24,8	20,0	18,6	17,5	29,5	31,0	19,7	15,0	12,8	17,0
		r _s		0,885		0,847		0,795		0,894		0,885		0,847		0,795		0,894
		p-value		0,000		0,000		0,000		0,000		0,000		0,000		0,000		0,000
	CON	M	74,9	79,0	105,5	82,0	94,9	77,0	90,7	84,0	83,9	66,0	88,9	86,0	88,8	78,0	99,3	82,0
IQR		20,0	13,0	18,2	12,5	24,9	9,0	17,3	22,5	21,9	17,5	16,3	16,5	22,2	7,5	19,7	14,8	
r _s			0,715		0,668		0,680		0,651		0,715		0,668		0,680		0,651	
p-value			0,000		0,001		0,001		0,001		0,000		0,001		0,001		0,001	
MVL	TPU	M	1,4	3,5	1,6	5,1	1,7	4,8	1,6	4,0	0,7	2,9	0,8	3,3	1,5	3,5	1,5	3,6
		IQR	1,4	2,2	1,9	2,9	0,9	2,9	1,5	2,5	0,8	2,3	0,8	2,8	1,2	2,7	1,5	3,2
		r _s		0,144		0,437		0,482		0,424		0,144		0,437		0,482		0,424
		p-value		0,533		0,048		0,027		0,056		0,533		0,048		0,027		0,056
	CON	M	1,4	4,5	2,5	6,0	2,0	6,7	2,9	4,8	0,8	4,0	1,6	5,5	2,0	7,1	2,4	6,2
IQR		1,2	2,8	1,5	4,4	1,0	4,9	2,2	2,2	1,1	2,7	1,9	3,5	1,2	4,8	2,2	3,6	
r _s			0,160		0,144		0,324		-0,104		0,160		0,144		0,324		-0,104	
p-value			0,488		0,533		0,152		0,654		0,488		0,533		0,152		0,654	

Table 3 - Group median (M) and interquartile range (IQR) for each of the variables: directional control (DCL), reaction time (RT), maximum excursion (MXE), and mean velocity (MVL) for the two groups (TPU & CON) for each of the goal directions (1-8). Goal directions normalized according to Figure 1, there 1=anterior, 2=anterior/intact, 3=intact, 4=posterior/intact, 5=posterior, 6=posterior/prosthesis, 7=prosthesis, 8=anterior/prosthesis. Spearman correlation coefficient (r_s) provided with p-value for the within-group correlation analyses for groups (TPU and CON): $DCL_{CoM}-DCL_{CoP}$, $RT_{CoM}-RT_{CoP}$, $MXE_{CoM}-MXE_{CoP}$, $MVL_{CoM}-MVL_{CoP}$. Bold text indicates statistically significant differences between TPU and CON.

3.3 Reaction times (RT_{CoP}) and the RTs derived from the and CoM (RT_{CoM}) and EMG

(RT_{EMG})

Statistically strong positive correlations were seen between the RT_{CoP} and RT_{CoM} for both the TPU and CON (r_s – TPU: 0.591, $p=0.000$; CON: 0.663, $p=0.000$). Statistically significant weak correlations were seen in the TPU for the GM, VL, and BF on the intact side and VL and BF on the affected side. The TPU also showed statistically significant weak correlations for ESL and ESR.

The CON exhibited statistically significant weak correlations for the VL on the left side and TA on the right side. Summary statistics given in Table 5.

Group		RT _{CoM}	Intact				Affected				ESL	ESR
			TA	GM	VL	BF	TA	GM	VL	BF		
TPU	M	1,39	0,15	0,22	0,16	0,17			0,18	0,26	0,23	0,23
	IQR	1,33	0,23	0,42	0,24	0,41			0,36	0,65	0,47	0,52
	r _s	0,591	0,062	0,204	0,209	0,217			0,168	0,163	0,292	0,169
	p-value	0,000	0,438	0,010	0,010	0,007			0,036	0,042	0,000	0,034
CON	M	1,80	0,14	0,20	0,17	0,22	0,13	0,19	0,18	0,20	0,21	0,20
	IQR	1,47	0,25	0,42	0,27	0,37	0,19	0,44	0,39	0,37	0,49	0,47
	r _s	0,663	0,134	-0,006	0,171	0,126	0,194	0,078	0,090	0,037	0,127	0,065
	p-value	0,000	0,086	0,939	0,029	0,116	0,012	0,327	0,253	0,653	0,109	0,404

Table 4 – Group median (M) and interquartile range (IQR) for. Spearman correlation coefficient (r_s) provided with p-value for the within-group correlation analyses for both groups (TPU and CON): All correlation coefficients and significance are based on analysis with the RT_{CoP}-RT_{CoM}, RT_{CoP}-RT_{EMG} (tibialis anterior (TA), gastrocnemius medialis (GM), vastus lateralis (VL), biceps femoris (BF), erector spinae – left side (ESL), erector spinae – right side (ESR).

4 Discussion

The aims of this study were to validate the outcome variables of the LoS protocol in transtibial prosthesis users via CoP data and movement of the CoM. An additional aim was to investigate the association between the reaction time as measured by movement of the CoP, CoM and that measured by EMG of the lower-extremity. Results indicate differences between the groups in association between movement of the CoP and CoM, the variables of the LoS protocol and the association between the reaction times amongst the CoP, CoM and EMG. Results suggest researchers should be cautious of which variables of the LoS protocol are used in analysis for individuals who use a prosthesis, specifically DC and MVL.

There was a statistically significant strong positive correlation between movement of the CoM and CoP in all of the directions, with the exception of the CON showing a statistically significant moderate positive correlation in the lateral direction (towards the right side) (median (IQR) = 0.61(0.52)). When looking at how the groups differed from each other there were three directions that resulted in significant differences between the ML- and AP-directions between the groups. All three of these differences were present when movements were directed towards

the intact limb (Goals 2_{AP}, 3_{ML}, and 3_{AP}). As previous research has shown, in quiet standing there is a strong association between the movement of the CoM and CoP in prosthesis users [20]. Yet, in the current study the subjects were asked to rapidly move their CoM towards the individual goals. This dynamic activity is substantially different than standing, and association between these two variables cannot be assumed without evidence. Although Aruin, et al. [10] utilized different methods than in the current study, they were able to show TPUs exhibited differences in coordination of mediolateral movements compared to controls. These authors showed that TPUs exhibited a longer phase shift of CoP between the initiation of movement and the maximum lateral position of the CoP. Although they did not incorporate CoM data in their analysis, it is possible the greater phase length of this shift of the CoP played a role in the differences seen in the current study, as this temporal difference between TPU and CON in lateral movement of the CoP would be exhibited in movements towards goals 2 and 3.

The LoS variables derived from the CoM and CoP showed statistically significant positive correlations from moderate (DCL and MVL) to strong (RT and MXE). This would seem to indicate that the measures that are extracted and presented by the forceplate reflect the same variables calculated based on the CoM. This is in itself a validation of the measures within this prosthesis user group. When the data was analyzed by direction it became clear there are differences present in the validity of the CoP and CoM when direction is taken into account. RT and MXE exhibited the highest correlations with all but two directions exhibiting statistically significant strong or moderate correlations (RT - TPU – goals 1 and 5 (0.42(0.06) & 0.42(0.06))). DCL and MVL exhibited non-statistically significant weak positive correlations in 4 of the 8 variables in the TPU. This suggests that researchers must be cautious in their interpretation of the DCL and MVL variables for the prosthesis user group. It is interesting to note results in the DCL and MVL for the control group showed weak non-significant correlations for all the directions. This calls into question the MVL and DCL variables ability

to describe movement of the CoM in this control group. As CoM and CoP are two related, but independent variables, and movement of the CoP being the body's physiological response to motions of the CoM [18], the results suggest that they may be measuring two different aspects of postural control in the current study. This could be due to the complex movement required during the LoS protocol, itself a challenge to the simple inverted pendulum model to describe postural control during standing [21] or a consequence of the definition of the outcomes, where RT and MXE are real numbers, and DCL and MVL are fractions making them sensitive to the magnitude of the denominator. Further research is warranted in order to determine if these results are generalizable or reflect only this sample group.

The calculated reaction time variables showed varying levels of association with each other. RT_{CoM} and RT_{CoP} clearly showed statistically strong positive correlations with each other for both the TPU and CON respectively (r_s – TPU: 0.591, $p=0.000$; CON: 0.663, $p=0.000$). In the TPU, RT_{EMG} variables exhibited statistically significant weak correlations for all of the variables except the tibialis anterior (TA) of the intact side. The CON exhibited two statistically significant weak correlations for the vastus lateralis (VL) and tibialis anterior (TA) (r_s – VL: 0.171, $p=0.029$; TA: 0.194, $p=0.012$). Effective reaction from appropriate muscles is required in order to coordinate body movements [27]. The fact that the TPU has a systematic weak correlation between the CoP variable and the individual muscle RT_{EMG} variables should not necessarily be seen as problematic. The CON exhibits very little correlation between the variables as it is possible that in some movements a short reaction time from the RT_{EMG} is actually counterproductive [27]. For instance in the type of reaction required to move from the center position to goal 1 a quick reaction from gastrocnemius would likely move the CoM posteriorly, something less optimal. In the same movement (towards goal 1) the TPU would likely require a short reaction time in the vastus lateralis on the affected side in order to stabilize the prosthetic side knee and drive the CoM forward. The reaction time variables are not directly

comparable and further research is suggested to understand the differences between the groups in their muscular reactions required to coordinate the same movement.

Certain limitations must be discussed. The statistical analysis was from the outset designed to be exploratory. For this reason adjustments for multiple comparisons were not utilized. The result is that the likelihood of Type I errors is greater. Had adjustments been made the likelihood for type II errors would have been greatly inflated, increasing the risk that important contrasts between variables would be missed [28,29]. Though, the exploratory results of the current study need be validated with more confirmatory research which encompasses appropriately focused research questions.

The current study utilized CoP data from a single forceplate. Although this means the contributions from individual feet cannot be separated, the movement of the global center of pressure has been validated as a measure of the movement of the center of mass in this group [20]. Though, one should be cautious to apply to the current results to the prosthetic limb as this has not been validated. The results from the CoP data are in line with previous data published regarding the LoS test variables for unilateral transtibial prosthesis users including reduced excursion towards the prosthetic limb and reduced mean velocities [15,17]. One should be conscious that an evaluation of these variables were not in line with the aims of this study, though it suggests valid data was used to address the aims of this study.

The results of this study suggest there is validity to the CoP variables extracted from the Limits of Stability protocol for unilateral transtibial prosthesis users. Though, researchers and clinicians need be aware that there is directional sensitivity to these variables that differ between TPUs and those who do not use a prosthesis. Rehabilitation staff should take into account these differences when designing protocols which intend of improving aspects of postural control.

5 Conclusion

Forceplate measures are valid in describing rapid and volitional movements of the center of mass for unilateral transtibial prosthesis users. Limits of stability outcomes extracted from center of pressure and center of mass data are highly correlated in some variables, but sensitive to direction in others. Muscular reaction time correlates very little with the reaction times extracted from the CoP and CoM data.

Conflict of interest statement

The author reports no conflicts of interest. The author alone is responsible for the content and writing of the paper.

References

1. de Sousa RF, Gazzola JM, Ganança MM, Paulino CA. Correlation between the body balance and functional capacity from elderly with chronic vestibular disorders. *Brazilian Journal of Otorhinolaryngology* 2011;77(6):791-798.
2. Scalzo PL, Flores CR, Marques JR, Robini SCdO, Teixeira AL. Impact of changes in balance and walking capacity on the quality of life in patients with Parkinson's disease. *Arquivos de Neuro-Psiquiatria* 2012;70:119-124.
3. Gremeaux V, Damak S, Troisgros O, Feki A, Laroche D, Perennou D, Benaim C, Casillas J-M. Selecting a test for the clinical assessment of balance and walking capacity at the definitive fitting state after unilateral amputation: a comparative study. *Prosthetics and Orthotics International* 2012;36(4):415-422.
4. Miller WC, Deathe AB, Speechley M, Koval J. The influence of falling, fear of falling, and balance confidence on prosthetic mobility and social activity among individuals with a lower extremity amputation. *Arch Phys Med Rehabil* 2001;82(9):1238-44.
5. Miller WC, Speechley M, Deathe B. The prevalence and risk factors of falling and fear of falling among lower extremity amputees. *Arch Phys Med Rehabil* 2001;82(8):1031-7.
6. Pauley T, Devlin M, Heslin K. Falls sustained during inpatient rehabilitation after lower limb amputation: prevalence and predictors. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists* 2006;85(6):521-32; quiz, 533-5.
7. Yu JC, Lam K, Nettel-Aguirre A, Donald M, Dukelow S. Incidence and Risk Factors of Falling in the Postoperative Lower Limb Amputee While on the Surgical Ward. *PM&R* 2010;2(10):926-934.
8. Mouchnino L, Mille ML, Cincera M, Bardot A, Delarque A, Pedotti A, Massion J. Postural reorganization of weight-shifting in below-knee amputees during leg raising. *Exp Brain Res* 1998;121(2):205-214.
9. Viton JM, Mouchnino L, Mille ML, Cincera M, Delarque A, Pedotti A, Bardot A, Massion J. Equilibrium and movement control strategies in trans-tibial amputees. *Prosthet Orthot Int* 2000;24(2):108-16.
10. Aruin A, Nicholas J, Latash M. Anticipatory postural adjustments during standing in below-the-knee amputees. *Clin Biomech* 1997;12:2 - 59.
11. Curtze C, Hof AL, Otten B, Postema K. Balance recovery after an evoked forward fall in unilateral transtibial amputees. *Gait Posture* 2010;32(3):336-341.
12. Barnett CT, Vanicek N, Polman RC. Postural responses during volitional and perturbed dynamic balance tasks in new lower limb amputees: A longitudinal study. *Gait & posture* 2012.
13. Brouwer B, Culham EG, Liston RA, Grant T. Normal variability of postural measures: implications for the reliability of relative balance performance outcomes. *Scand J Rehabil Med* 1998;30(3):131-7.
14. Hageman PA, Leibowitz JM, Blanke D. Age and gender effects on postural control measures. *Arch Phys Med Rehabil* 1995;76(10):961-5.
15. Molero-Sánchez A, Molina-Rueda F, Alguacil-Diego IM, Cano-de la Cuerda R, Miangolarra-Page JC. Comparison of Stability Limits in Men With Traumatic Transtibial Amputation and a Nonamputee Control Group. *PM&R* 2015;7(2):123-129.

16. Rusaw D, Nolan L, Hagberg K, Ramstrand N. Can vibratory feedback be used to improve postural stability in persons with transtibial limb loss? *Journal of Rehabilitation Research and Development* 2012;In Press.
17. Kolarova B, Janura M, Svoboda Z, Elfmark M. Limits of Stability in Persons With Transtibial Amputation With Respect to Prosthetic Alignment Alterations. *Archives of Physical Medicine and Rehabilitation* 2013;94(11):2234-2240.
18. Gage WH, Winter DA, Frank JS, Adkin AL. Kinematic and kinetic validity of the inverted pendulum model in quiet standing. *Gait & posture* 2004;19(2):124-32.
19. Winter DA, Prince F, Frank JS, Powell C, Zabjek KF. Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology* 1996;75(6):2334-2343.
20. Rusaw DF, Ramstrand S. Validation of the Inverted Pendulum Model in standing for transtibial prosthesis users. *Clin Biomech* 2016;31:100-6.
21. Kilby MC, Molenaar PCM, Newell KM. Models of Postural Control: Shared Variance in Joint and COM Motions. *PLoS ONE* 2015;10(5):e0126379.
22. Buczek FL, Cooney KM, Walker MR, Rainbow MJ, Concha MC, Sanders JO. Performance of an inverted pendulum model directly applied to normal human gait. *Clinical Biomechanics* 2006;21(3):288-296.
23. Shih Y, Chen Y-C, Lee Y-S, Chan M-S, Shiang T-Y. Walking beyond preferred transition speed increases muscle activations with a shift from inverted pendulum to spring mass model in lower extremity. *Gait & Posture* 2016;46:5-10.
24. Dempster T. Space requirements of the seated operator: geometric, kinematic, and mechanical aspects of the body with special reference to the limbs. Springfield, Ohio.: Wright Air Development Center Air Research and Development Command; 1955. 274 p.
25. Neurocom International I. Balance Manager Systems - Clinical Operations Guide. 2008. p 9.
26. Winter DA. *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons, Inc.; 2009. 370 p.
27. Nashner LM. Adapting reflexes controlling the human posture. *Exp Brain Res* 1976;26(1):59-72.
28. Perneger TV. What's wrong with Bonferroni adjustments. *BMJ* 1998;316(7139):1236-1238.
29. Rothman KJ. No adjustments are needed for multiple comparisons. *Epidemiology* 1990;1(1):43-6.