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Full Length Article

Variability in trunk and pelvic movement of transfemoral amputees using a C-leg system compared to healthy controls

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ABSTRACT

Objective: Gait variability is a measure of gait disturbance, and therefore constitutes a useful parameter for gait assessment as well as planning of therapeutic and medical interventions. To date, variability during walking has not been adequately analyzed in amputees. The aim of this examination was to evaluate trunk and pelvic movement variability in transfemoral amputees. The effect of different types of walking surfaces on variability in trunk and pelvic movement was also studied.
Method: This prospective clinical examination compares 20 transfemoral amputees (17 ♂, 42 ± 16 years; 3 ♀, 48 ± 3 years) with a group of 20 age and mass matched healthy controls regarding the extent of variability in trunk and pelvic movement. Kinematic data of trunk and pelvic movement during walking on level, uneven ground and slope was captured by eight infrared cameras (Vicon Nexus ™, Oxford, UK). Variability in trunk and pelvic movement was analyzed. Univariate ANCOVA and ANOVA with repeated measures and post hoc tests were used for statistical comparison. Fall history was retrospectively collected from medical history to assess the association between falls and variability in trunk and pelvic movement.
Results: Trunk and pelvic movement variability in amputees was significantly higher during walking on uneven ground and slope compared to healthy controls ($p \leq 0.05$). Variability in trunk and pelvic movement was increased during walking on uneven ground and slope compared to even ground for both groups ($p \leq 0.05$).
Conclusion: Amputees showed increased trunk and pelvic movement variability during walking on uneven ground and slope, indicating an affected gait pattern in comparison to healthy controls. Therefore, trunk and pelvic movement variability could be a potential marker for gait quality with diagnostic implications.

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1. Introduction

Individuals who have lost a limb after trauma, arterial disease or sarcoma must cope with significant functional impairment as well as mental disorder (Narang, Mathur, Singh, & Jape, 1984; Greive & Lankhorst, 1996; MacKenzie et al., 2004; Sinha, van den Heuvel, & Arokiasamy, 2011). Every second individual with unilateral lower limb amputation reports at least one fall per year (Miller, Speechley, & Deathe, 2001). 49% of these patients expressed a fear of falling, and 76% avoid activities because of their fear of falling (Miller et al., 2001). Additional loss of the knee joint due to amputation further reduces movement control and stability during standing (Ku, Osman, & Abas, 2014). To achieve sufficient walking stability for transfemoral amputees, therapeutic treatments and prosthetic adaptations need to be optimized and customized on an individual basis. Thus, there is a need for an objective assessment of gait pattern and walking stability.

One factor which has been suggested as a measure of gait disturbance in several studies is gait variability. Risk of falling as well as fear of falling have shown to be associated with increased gait variability (Ayoubi, Launay, Annweiler, & Beauchet, 2014; Sawa et al., 2014). Furthermore, in patients with lower limb amputation and a history of falling, a large variation of swing duration was found (Vanicek, Strike, McNaughton, & Polman, 2009). However, there are also studies which present contrary results and show no differences in gait variability of amputee fallers and non-fallers (Parker, Hanada, & Adderson, 2013). All of these previous studies, which focused on gait variability in amputees and highlight the importance of this parameter, only considered the variability of spatio-temporal parameters such as gait velocity, step width or step length, but not any kinematic parameters such as joint angles or body postures. Kinematic data are inherently more challenging to collect and assess compared to spatio-temporal parameters; however, they may provide more detailed information about body movement, posture, gait pattern repeatability and stability beyond those obtained from spatio-temporal gait parameters alone. Kinematic data is able to describe humans` gait pattern and its quality in a very detailed way (Whittle, 1996). In particular, trunk movement variability during walking has been shown to be associated with a decreased gait stability and an increased fear of falling in the elderly (Sawa et al., 2014; Toebes, Hoozemans, Furrer, Dekker, & van Dieën, 2012). However, there is a lack of published literature that analyzes trunk movement variability or other kinematic data in lower limb amputees. The inconsistency of previous literature findings regarding gait variability in lower limb amputees (Lin, Winston, Mitchell, Girlinghouse, & Crochet, 2014; Parker et al., 2013; Vanicek et al., 2009) may possibly result from the exclusive use of spatio-temporal parameters neglecting analysis of kinematic data. It may be possible that spatio-temporal parameter variability is not statistically significant enough to present clear results. Furthermore, most previous literature is only focused on walking on even ground (Lin et al., 2014; Parker et al., 2013; Svoboda, Janura, Cabell, & Elfmark, 2012; Vanicek et al., 2009). There is a need, however, for detailed gait analysis to be conducted on uneven ground to assess lower limb amputees' ability to handle more challenging terrains which simulate outdoor walking. Walking on different types of surfaces poses exacerbated challenges and might thus be more sensitive for the detection of gait variability, but to our knowledge has not yet been analyzed.

The aim of this study was to compare the variability of lateral trunk bending and pelvic obliquity during walking in amputees to healthy controls. We further analyzed to which extent variability is affected by different walking surfaces. We hypothesized that kinematic variability during walking is increased in amputees using a prosthetic knee joint system compared to healthy controls, and that variability is further increased during walking on uneven ground or on slope in comparison to walking on even ground.

2. Methods

2.1. Participants

This prospective clinical examination study received approval by the responsible ethical committee (Ethikkommision der Bayerischen Landesärztekammer, Germany, No. 13131) and complies with the principles outlined in the Declaration of Helsinki. All test persons were informed about the procedure as well as their rights and gave written consent prior to participation in our study. A group of 20 transfemoral amputees using the C-leg knee-joint system (Ottobock, Duderstadt, Germany) were recruited for this study during their hospital stay and were compared to 20 healthy controls matched for age (± 5 y), height (± 5 cm), and mass (± 5 kg). Amputees were hospitalized for assessment of their prosthetic treatment. Time since amputation in patients was 16 years ± 12 years. We calculated that a sample size of 14 participants per group provided 80% power ($\beta = 0.20$) to detect a difference of ± 1 standard deviation for the parameters variability in pelvic obliquity and lateral trunk bending between both groups, assuming a significance level of 5% ($\alpha = 0.05$) (Faul, Erdfelder, Lang, & Buchner, 2007).

Inclusion criteria were: age between 18 and 65 years, unilateral transfemoral amputation or knee-disarticulation, use of the microprocessor-controlled prosthetic knee C-leg 2 or 3 (Ottobock, Duderstadt, Germany), suction socket type with valve or seal-in technique or a liner with pin and an ischial containment socket shape for transfemoral amputees and a suction socket type with seal-in technique for knee disarticulation. Additionally, all amputees had to show the ability to walk without walking aids other than the prosthesis in everyday life and had to be appropriately accustomed to wearing and walking with the C-leg system. The inclusion criteria also demanded a correct prosthetic alignment as well as an acceptable socket fit. These basic settings were checked in a medical entry examination (Table 1).

2.2. Procedure

All test persons participated in gait analysis walking trials using an eight infrared-camera motion analysis system (Vicon™, Oxford, UK). Thirty retro-reflective markers (14 mm diameter) were fixed on the lower limbs and the upper body following anatomical

Table 1
Description of study sample (group of transfemoral amputees $n = 20$ and healthy controls n = 20).

	Patients		Healthy test persons	
Gender	17♂	3 ♀	17♂	3 ♀
Age	42 y ± 16 y	48 y ± 3 y	43 y ± 11 y	48 y ± 5 y
Weight	93 kg ± 11 kg	65 kg ± 11 kg	92 kg ± 14 kg	62 kg ± 7 kg
Height	183 cm ± 6 cm	166 cm ± 3 cm	186 cm ± 7 cm	170 cm ± 5 cm
Transfemoral	12	3		
Knee-disarticulation	5	0		

landmarks according to the conventional gait model of Kadaba, Ramakrishnan, and Wootten (1990) and the guidelines of Vicon™ (Plug-in Gait Reference Guide, 2016) (Fig. 1).

Lower limb and upper body data were recorded at 200 Hz. Marker data were filtered using a Woltring filter with a predicted mean square error value of 10 mm^2 (Woltring, 1986). Kinematic data of trunk and pelvic movement of all participants from both groups were measured in four walking conditions: even and uneven ground, inclined and declined slope. The uneven ground was simulated by structural panels (Terrasensa®-plates, Hübner, Kassel, Germany) over a distance of 6 m. Walking on inclined and declined slope

Fig. 1. Marker placement (Plug-in Gait Fullbody model). Markers on the prosthetic system were placed at the same positions as on the intact limb. Upper body: C7 (Spinous process of C7); TH 10 (Spinous process of TH 10); RBAK (Centrical on the right scapula); CLAV (Jugular Notch); STRN (Xiphoid process of the sternum); LSHO and RSHO (Acromio-clavicular joint left/right); LELB and RELB (Lateral epicondyle left/right); LWRA and RWRA (Process styloideus radii left/right); LASI and RASI (Anterior superior iliac spine left/right); SACR (Sacrum).
Lower limbs: LTHI and RTHI (surface of the left/right thigh); LKNE and RKNE (flexion-extension axis left/right knee); LTIB and RTIB (surface of the left/right shank); LANK and RANK (lateral malleolus left/right); LHEE and RHEE (calcaneous left/right at the same height above the plantar surface of the foot as the toe marker); LTOE and RTOE (second metatarsal head).

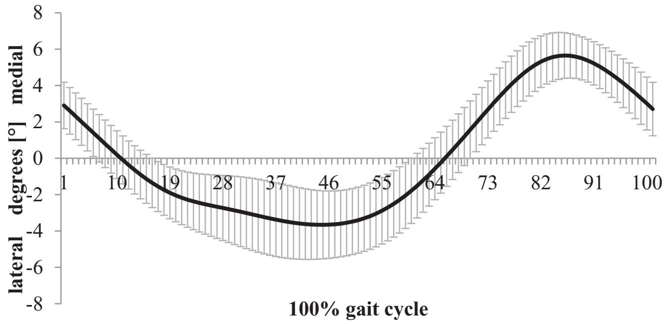


Fig. 2. Kinematic data of lateral trunk bending to the healthy side of one amputee while walking on even ground with variability indicated by the standard deviation. The averaged width standard deviation band constitutes the variability.

was facilitated by a mobile ramp, which had a length of 3 m.

Each of the four walking conditions started with two warm up trials to allow the subject to become familiar with the different surface types. Afterwards, each test person was instructed to complete five trials of each walking conditions. For healthy participants, kinematic data of trunk and pelvic movement as well as spatio-temporal parameters were measured and analyzed on the same side of the body as their matched amputee.

To determine the variability of gait as a measure of gait stability, kinematic data of trunk and pelvic movement were analyzed in the frontal plane. Previous literature clearly shows that evasive movements in trunk and upper body may be associated with an increased instability of gait in the elderly (Sawa et al., 2014; Toebes et al., 2012). Therefore, this study focuses on kinematic data of trunk and pelvic movement and not of the lower limbs.

Trunk and pelvic movement kinematic data were time normalized to 100% gait cycle and interpolated to 100 data points (Matlab R2013a, The Mathwork Inc., Natick, MA. USA). For each data point, the standard deviation was computed over five trials within each condition. To estimate gait variability in trunk and pelvic movement, standard deviations (σ_i) over all data points were multiplied by two and averaged (Eq. (1)) (Fig. 2):

$$variability = \left(\sum_{i=1}^{100} 2\sigma_i\right)/100 \tag{1}$$

Schwartz et al. showed that kinematic data variability could be influenced by spatio-temporal parameters such as gait velocity (Schwartz, Rozumalski, & Trost, 2008). To ensure that measured trunk and pelvic movement variability was not influenced by spatio-temporal parameters, gait velocity and step length were also examined in this study.

Occurrence of falls in amputees was retrospectively assessed by interview.

2.3. Data analysis

For statistical analysis, univariate ANCOVA was used to compare amputees and healthy controls regarding trunk and pelvic movement variability in different walking conditions. Gait velocity and step length were included as co-factors to minimize the likelihood of any influencing factors. Additionally, a Student's *t*-test was used to compare the group of amputees and healthy controls regarding gait velocity and step length. For further analyses, univariate ANOVA with repeated measures and Bonferroni-adjusted post-hoc tests were used to compare the effect of different surface conditions on pelvis obliquity and lateral trunk bending variability. The significance level was set at $\alpha = 0.05$. All statistical analyses were performed using SPSS software (IBM SPSS 19, IBM Corp., Armonk, NY, USA). Additionally, standard error of mean (SEM) and minimal detectable change ($MDC = SEM \times 1.96 \times \sqrt{2}$) for variability in trunk and pelvic movement were analyzed.

3. Results

3.1. Spatio-temporal parameters: comparison between the group of amputees and healthy controls

Step length (11% even ground: $p = 0.004$; 14% uneven ground: $p = 0.001$; 14% inclined slope: $p = 0.001$; 11% declined slope; $p = 0.004$) and gait velocity values during walking (14% even ground: $p = 0.001$; 26% uneven ground: $p \leq 0.001$; 24% inclined slope: $p \leq 0.001$; 21% declined slope; $p \leq 0.001$) were significantly smaller in amputees compared to healthy controls. Thus, the statistical analysis comparing variability between the group of amputees and healthy controls was adjusted for these parameters.

3.2. Variability of pelvic obliquity and lateral trunk bending: comparison between the group of amputees and healthy controls

Variability in pelvic obliquity was consistently larger in amputees compared to controls (Fig. 3 a.). The differences were most pronounced during walking on uneven ground (81%, $p = 0.006$; MDC = 0.8°), inclined slope (85%, $p < 0.001$; MDC = 0.8°) and

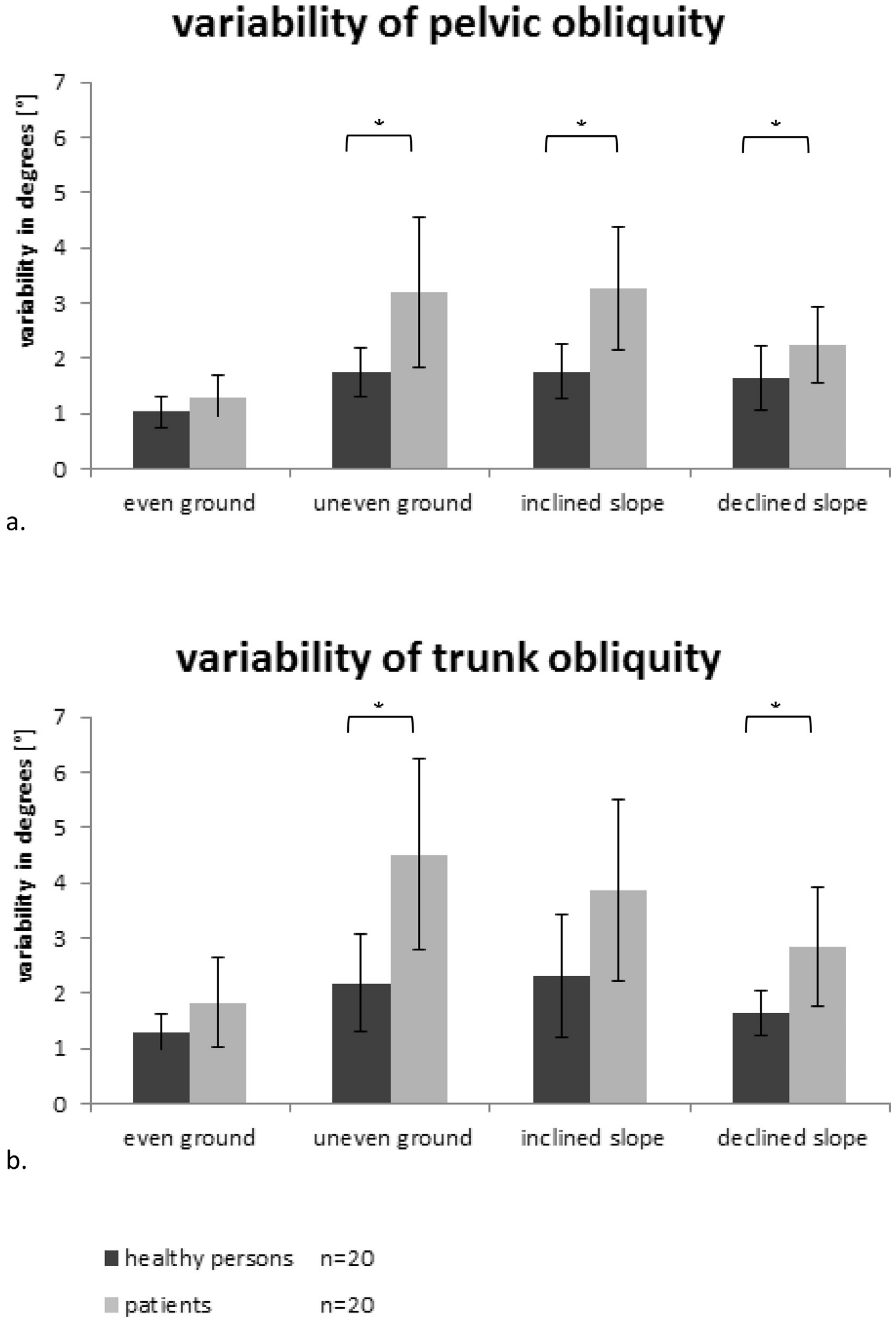


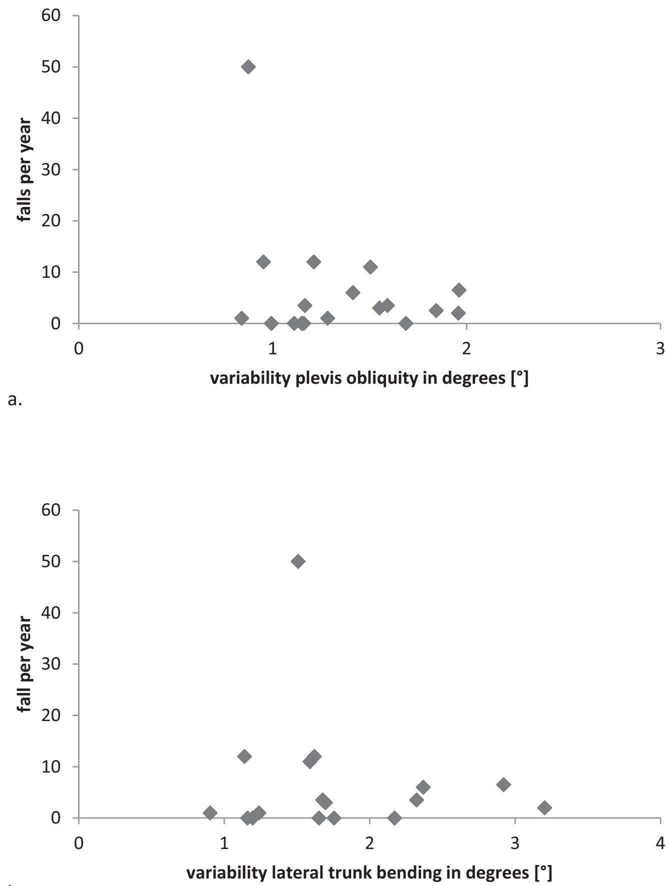
Fig. 3. Means and standard deviations of variability of pelvic obliquity (a.) and lateral trunk bending (b.) in healthy controls and amputees during walking on different types of surfaces, *: $p < 0.05$.

declined slope (36%, $p = 0.03$; MDC = 2.2°) (Fig. 3 a.). No significant differences between both groups were found during walking on even ground (25%; $p = 0.089$; MDC = 0.25°). Also, trunk variability was consistently larger in amputees compared to controls (Fig. 3 b). Again, the differences were most pronounced during walking on uneven ground (105%, $p = 0.006$; MDC = 1.1°), and on a declined slope (73%, $p = 0.001$; MDC = 0.6°) (Fig. 3 b.). No significant differences between amputees and healthy controls were found during walking on even ground (53%; $p = 0.113$; MDC = 0.5°) or on inclined slope (66%; $p = 0.077$; MDC = 1.1°).

3.3. Variability of pelvic obliquity and lateral trunk bending: comparison between different walking conditions

Pelvic obliquity variability was increased during walking on uneven ground (amputees: $p \leq 0.001$; healthy controls: $p \leq 0.001$), on inclined (amputees: $p \leq 0.001$; healthy controls: $p \leq 0.001$) and on a declined slope (amputees: $p \leq 0.001$; healthy controls: $p = 0.002$) when compared to even ground for both groups. Among the three challenging walking conditions, amputees demonstrated no differences between walking on uneven ground and inclined slope ($p = 1.0$), but exhibited a higher variability while walking on uneven ground ($p = .049$) and on an inclined slope ($p = 0.016$) compared to walking on declined slope. However, healthy controls showed no differences in variability between any of the walking conditions uneven ground, inclined slope and declined slope ($p = 1.0$).

Lateral trunk bending variability was increased during walking on uneven ground (amputees: $p \leq 0.001$; healthy controls: $p = 0.001$), inclined (amputees: $p \leq 0.001$; healthy controls: $p = 0.005$) and declined slope (amputees: $p = 0.003$; healthy controls: $p = 0.012$) when compared to walking on even ground for both groups. Among the three challenging walking conditions both groups demonstrated a significantly higher variability on uneven ground compared to declined slope (amputees: $p = 0.001$; healthy controls: $p = 0.04$). Neither group showed differences in variability during walking on an inclined slope compared to walking on uneven ground or (amputees: $p = 0.1$; healthy controls: $p = 0.1$) on a declined slope (amputees: $p = 0.178$; healthy controls: $p = 0.096$).



a.

b.

Fig. 4. Association between amputees` falls per year and the variability during walking on even ground in pelvic obliquity (a.) and lateral trunk bending (b.)

3.4. Association to history of falling in amputees

Amputees reported between 0 and 12 falls per year, with one patient reporting 50 falls over the last year. The number of reported annual falls showed no association with variability, in either the pelvis or the trunk (Fig. 4).

4. Discussion

The findings from our study suggest that variability of kinematic gait parameters is larger in amputees using a prosthetic knee joint system compared to healthy controls during walking on uneven ground or on slope. However, larger trunk and pelvic movement variability in amputees was not associated with an increase in fall tendency.

Previous literature shows that regularity and reproducibility of gait is the basis for a stable and confident gait pattern; every step can be anticipated and the motion sequence occurs completely automated (Kadaba et al., 1989; Growney, Meglan, Johnson, Cahalan, & An, 1997; Sawa et al., 2014; Ayoubi et al., 2014). Whenever walking starts to become irregular, it may lead to an unstable gait pattern with an increased risk of falling (Ayoubi et al., 2014; Sawa et al., 2014; Toebes et al., 2012). However, our data is unable to show any association between falls and variability during walking such as demonstrated in previous literature analyzing amputees or older people (Vanicek et al., 2009; Toebes et al., 2012).

Further studies reported no increased number of falls but rather an increased risk of falls and an increased fear of falling in patients with higher variability (Ayoubi et al., 2014; Sawa et al., 2014; Toebes, Hoozemans, Furrer, Dekker, & van Dieën, 2015). An increased fear of falling may lead to inactivity, which in turn could result in a lower quality of life and further health problems (Miller et al., 2001). Previous literature also demonstrates that transfemoral amputees with increased kinematic variability show lower levels of daily activity (Müßig et al., 2019). Therefore, it may be possible that patients with a high extent of variability did not necessarily demonstrate a high number of falls. Nevertheless, increased variability could indicate a deficit in stability and balance during walking and standing (Beauchet et al., 2009; Lamoth, Ainsworth, Polomski, & Houdijk, 2010). An unstable gait pattern can intensify the fear of falling and consequently decrease both daily activity and the quality of life (Lamoth et al., 2010; Terrier & Reynard, 2015; Toebes et al., 2015). Thus, the assessment of variability in gait pattern of transfemoral amputees could potentially be of clinical relevance. Our results clearly demonstrate that amputees show significant abnormalities in kinematic variability and therefore limitations in their walking quality and stability in comparison to healthy controls. Further research studies should clarify to which extent therapeutic approaches and orthopaedic treatments can be optimized and individually improved based on trunk and pelvic movement variability data.

Potential co-factors such as step length or gait velocity had no influence on trunk and pelvic movement variability during gait. Thus, our findings suggest that increased trunk and pelvic movement variability in amputees results from an irregular motion sequence during walking and is not associated with spatio-temporal parameters.

A limitation of this study is the retrospective retrieval of fall history. Retrospective reports of fall occurrence tend to be biased by expectation and by the subjective fear of falling. Nevertheless, our data suggest that, within our group of amputees, trunk and pelvic movement variability does not explain the occurrence of falls. Other factors not assessed in this study like activity level and type of activity might be more important factors associated with falls. Another general limitation of gait laboratory based analyses of gait pattern is the unfamiliar laboratory environment and spatial limitation of gait distances, in particular for walking on a slope. We tried to minimize these factors by providing ample time for participants to become accustomed to the laboratory environment.

Despite these limitations, our study demonstrates a novel approach in the research of lower limb amputees and is one of the very few examinations in the literature analyzing variability in amputees in this way. In previous literature, the regularity and reproducibility of gait pattern is only rarely analyzed in amputees. Furthermore, only the variability of spatio-temporal parameters, kinetic data or acceleration data were analyzed (Lamoth et al., 2010; Parker et al., 2013; Svoboda et al., 2012; Vanicek et al., 2009). Therefore, our study clearly demonstrates kinematic variability in transfemoral amputees walking on different types of surface compared to healthy controls. A further strength of our study is the very homogeneous group of amputees compared to previous literature, which examined more heterogeneous amputee groups (IJmker et al., 2014; Lamoth et al., 2010; Lin et al., 2014; Parker et al., 2013; Sagawa Jr. et al., 2011; Tanimoto, Anan, Sawada, Takahashi, & Shinkoda, 2016; Vanicek et al., 2009).

Tanimoto et al. (2016) acknowledged in their study that kinematic data variability could be a useful marker to assess gait pattern in healthy persons. Our study analyzed variability in trunk and pelvic movement in the frontal plane during walking. We intentionally decided to examine these parameters and not the kinematic data of lower limbs, on neither the intact limb nor the prosthetic side. Trunk and pelvis generate one entire unit of the body and represent the movement of the upper body in space. Additionally, trunk movement variability during walking has been shown to be associated with a decreased gait stability and an increased fear of falling in the elderly (Sawa et al., 2014; Toebes et al., 2012). Therefore, we determined kinematic data of trunk and pelvis motion to be most appropriate for our analyses.

In addition, we analyzed the influence of spatio-temporal parameters as well as the effect of different types of surfaces on variability in trunk and pelvic movement. These issues have not yet been adequately investigated in previous literature (Gates, Dingwell, Scott, Sinitski, & Wilken, 2012; Parker et al., 2013; Sawa et al., 2014).

Lastly, amputees wearing a C-leg system demonstrated an increased variability in trunk and pelvic movement during walking on uneven ground and slope.

5. Conclusion

This study analyzed kinematic variability in amputees in different walking conditions. Transfemoral amputees clearly demonstrated increased kinematic variability in trunk and pelvic movement, indicating that their gait pattern is affected in comparison to healthy controls. Therefore, variability in trunk and pelvic movement during walking could be a potential marker for gait quality with diagnostic implications.

Declaration of Competing Interest

All authors declare that they do not have any conflicts of interest.

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