Abstract

Background: Gait in people with lower limb amputation (LLA) is typically asymmetrical. Reducing this asymmetry is often attempted to minimise the impact of secondary health issues. However, temporal-spatial asymmetry in gait of people with LLA has also been shown to underpin dynamic stability.

Research Question: The current study aimed to identify the effects of acute attempts of temporal-spatial symmetry on the dynamic stability of people with unilateral transtibial amputation (UTA). The secondary aim of this study was to identify the corresponding biomechanical adaptations during attempted symmetrical gait.

Methods: Eleven people with UTA walked along a 15m walkway in four different conditions, normal (NORM), attempted symmetrical step length and step frequency (SYM_{SL+SF}) attempted symmetrical step length (SYM_{SL}) and attempted symmetrical step frequency (SYM_{SF}). Dynamic stability was measured using the backward (BW) and mediolateral (ML) margins of stability (MoS).

Results: The results suggested that attempting symmetrical step frequency had a positive effect on gait stability in anterior-posterior and medio-lateral directions, while attempting symmetrical step length had a potentially negative effect on gait stability, although these results did not appear to be significant. An absence of clustering in PCA, supported the lack of significant results indicated no features differentiating between conditions of attempted symmetry compared to habitual gait. Conversely, there was a clustering by limbs which were associated with differences in knee and ankle joint angles between the intact and prosthetic limb, and clustering by individuals highlighting the importance or subject-specific analysis.

Conclusion: The data suggests that attempted symmetrical gait reduced asymmetry but also affects dynamic stability.

Introduction

People with lower limb amputation (LLA) are known to fall more often relative to age-matched, control participants (Miller *et al.*, 2001; Miller, Speechley and Deathe, 2001). Although falling is a significant problem, its underlying mechanisms in people with LLA are not fully understood (Curtze *et al.*, 2010). In general, people with LLA tend to have lower walking speeds, smaller step frequencies, and longer step widths and step length (Schmid-Zalaudek *et al.*, 2022) although there is some inconsistency in the literature with regards to the step length whether it is longer (Isakov, Keren and Benjuya, 2000), shorter (Highsmith *et al.*, 2010) or similar (Hak *et al.*, 2014). As these temporal-spatial gait characteristics influence a person's dynamic stability, altering them could affect dynamic stability and subsequently increase fall's risk.

The margin of stability (MoS) is a measure used to quantify dynamic stability (Hof, Gazendam and Sinke, 2005; Hof *et al.*, 2007), and it can be defined in anterior-posterior (AP) and mediolateral (ML) directions, with a greater MoS implying greater stability. People with LLA have smaller posterior or backward (BW) MoS relative to control participants but have larger ML MoS (Hak, van Dieën, *et al.*, 2013) which is likely due to the wider step length. This could be a compensatory mechanism to maintain stability and minimise the risk of falling.

Asymmetrical gait in people with LLA can be viewed as undesirable, as it is associated with secondary health issues such as hip and knee osteoarthritis (Gailey *et al.*, 2008). Thus, during prosthetic rehabilitation, gait symmetry is often sought after to minimise the risk of developing these secondary issues. However, the effects of trying to achieve a more symmetrical gait on gait stability are unknown. Previous literature indicates that temporal-spatial asymmetry might play a functional role in the stability of people with LLA (Hak *et al.*, 2014). A shorter step length on the intact limb is said to contribute to a larger BW MoS at heel strike of the intact limb. Therefore, temporal-spatial asymmetry aids to maintain a stable MoS (Bolger, Ting and Sawers, 2014; Hak *et al.*, 2014) which may help decrease the risk of falling. Therefore, the primary aim of this study was to identify the effects of acute attempts for temporal-spatial symmetry on the dynamic stability of high-functioning people with unilateral transtibial amputation (UTA). The secondary aim of this study was to identify the biomechanical adaptations made by people with UTA during acute attempts of temporal-spatial symmetry.

Methods

Participants

A convenience sample of eleven people with UTA were recruited from a local prosthetic centre (Table 1). All individuals wore their own prosthesis and were able to walk unaided for at least three minutes. Ethical approval for this study was granted by a National Health Service Research Ethics Committee (REC reference: XX/XX/XXXX). All participants provided written informed consent prior to participation.

Insert Table 1. here

Experimental Design

Participants visited the laboratory on two occasions and completed walking trials under four conditions. During visit 1, participants walked at a ‘normal’ self-selected speed (NORM) during which time habitual step length and step frequency were measured (Figure 1a). The habitual step length and step frequency were used to compute symmetrical step length and step frequency for visit 2. The symmetrical step length of each limb was calculated using the sum of intact and prosthetic step lengths divided by two. The symmetrical step frequency was calculated from the sum of intact and prosthetic step frequencies divided by two. To indicate the symmetrical step length and step frequency, floor markings and a metronome were used, respectively. During visit 2, participants walked with attempted symmetrical step length and step frequency (SYM_{SL+SF}) (Figure 1b), attempted symmetrical step length (SYM_{SL}) (Figure 1c), and attempted symmetrical step frequency (SYM_{SF}) (Figure 1d). The final three conditions were randomised across participants.

Insert Figure 1 here

Experimental Trials

Five successful trials, defined as good contact between the participant's foot and the force plate, were collected for both limbs in each condition. During SYM_{SL} condition, participants were required to place their heel on the floor markings along the length of the walkway (15m). During SYM_{SF} condition, participants were required to step in time with the sound of a metronome and during SYM_{SL+SF} participants were required to place their heel on the floor markings in time with the sound of a metronome.

Data Collection

To measure whole-body kinematics, 70 spherical 14mm, reflective markers were placed directly onto the skin or clothing using bi-adhesive tape, defining the head, arms, trunk as detailed by Leardini et al., 2011 and lower limb segments as detailed by Cappozzo et al., 1995. Kinematics were measured using a nine-camera motion capture system (Oqus, Qualisys, Gothenburg, SE) sampling at 100 Hz, and ground reaction force (GRF) was measured using a single floor-mounted strain gauge force platform (AMTI, Watertown, MA, USA) sampling at 1000Hz.

Data Analysis

To address the primary aim, temporal-spatial symmetry was defined using step length and step frequency data with dynamic stability quantified using BW and ML MoS. To define the MoS, a kinematic approach was taken (Hak *et al.*, 2012) based upon an original kinetic definition (Hof, Gazendam and Sinke, 2005). Where the posterior border was defined by the marker on the heel whilst the lateral border was defined by the marker on the lateral malleoli. The whole-body centre of mass position was estimated using a kinematic model derived from a full body marker set described above (Cappozzo et al., 1995; Leardini et al., 2011) in Visual 3D v5 (C Motion, Inc., Germantown, MD, USA). To address the second aim, twenty variables commonly reported in the literature for forward progression and dynamic stability were assessed - GRF components, centre of pressure displacements and velocities, vertical centre of mass displacement and velocity, sagittal plane hip, knee and ankle joints powers, moments and angles. These parameters were selected since the continuous interchange between mobility and stability are essential for efficient walking (Lakany, 2008).

The power on the prosthetic limb was computed using a unified deformable segment approach (Takahashi, Kepple and Stanhope, 2012). For each trial, a minimum of three gait cycles were extracted for each limb. Kinematic data were interpolated using a cubic-spline algorithm, and the kinematic and GRF data were low-pass filtered with a fourth-order, bi-directional Butterworth filter with cut-off frequencies of 6Hz and 30Hz, respectively. All data were normalised to 100% of the gait cycle. Medial and lateral landmarks defined anatomical frames from which segment coordinate systems were defined following the right-hand rule (Cappozzo *et al.*, 1995). A flexion-extension, abduction-adduction and longitudinal cardan rotation sequence were used to define the order of rotations to calculate joint kinematics. Gait events of heel strike (HS) and toe-off (TO) were determined using GRFs where available and otherwise using previously reported kinematic algorithms (Stanhope *et al.*, 1990; Zeni, Richards and Higginson, 2008).

Statistical Analysis

For variables with no inter-limb comparisons e.g. walking speed, a one-way repeated measures analysis of variance (ANOVA) was used to compare conditions (NORM, $\mathrm{SYM}_{\mathrm{SL+SF}}$, $\mathrm{SYM}_{\mathrm{SL}}$ and $\mathrm{SYM}_{\mathrm{SF}}$). For variables with an additional inter-limb comparison, a limb main effect was added (PROS and NONPROS), as well as a limb by condition interaction effect within a two-way repeated measures ANOVA. The normality of data was assessed using the Shapiro-Wilk Test. Effect sizes (partial eta squared, η_p^2) were calculated for each statistical comparison with small, moderate and large effect size, being defined as r = 0.10, r = 0.30 and r = 0.50, respectively (Field, 2005). Post-hoc comparisons were corrected using a Bonferroni adjustment. The alpha level (α) of statistical significance was set at $p <$ 0.05. All statistical analyses were conducted in IBM SPSS v.24 (IBM, Portsmouth, UK).

Principal component analysis (PCA) was applied to the biomechanical variables to identify which gait adaptations were present in each of the experimental conditions. This analysis allows multiple variables to be examined simultaneously, which can help identify the causal factors contributing to differences observed between specific conditions. By considering various variables together, it becomes possible to gain insights into the relationships and influences among them, ultimately providing a clearer understanding of the factors influencing the observed differences.

Both the covariance and the correlation approaches of PCA were used to identify differences in the data with regards to variation and magnitude, respectively. During gait, biomechanical measurements are derived from varying joints, where some will naturally exhibit larger magnitudes than others due to anatomical and biomechanical characteristics, e.g. the hip joint moves through a larger range of motion in comparison to the ankle joint. Furthermore, some variables have different units of measurement, thus, prior to the application of PCA, biomechanical data needs to be normalised. This is done by maximising the variables with the same units to the same absolute. In the 'normal' covariance PCA approach, the parameters that exhibit larger deviations will naturally be more dominant in comparison to those parameters that exhibit little variation, e.g. the ankle joint angle will inherently provide more emphasis than the hip joint angle. Since parameters exhibiting smaller deviations may also carry important information such as the hip joint angle in the example above, in the correlation approach data is divided (or 'scaled' or 'normalised') by its own standard deviation prior to analysis, resulting in equal contribution coming from the hip joint angle and the ankle joint angle. Hence, in the case of the correlation PCA approach, these inherent differences will be compensated for. With regards to the covariance approach the classification of the data is due to the variance, whilst using the correlation approach the classification is due to magnitude. One approach is no better than the other (in particular, note that small deviations carried in meaningless 'noise' or 'artefacts' are likely to be exacerbated in the correlation PCA) but each brings different insight in the understanding the data.

Results

For all conditions, BW MOS was larger on the NONPROS limb relative to the PROS limb, reflected in a statistically significant limb effect (F(1,10) = 11.44, p = 0.007, η_p^2 = 0.534) (Figure 2a). There was also a statistically significant condition effect in BW MoS (F(1.47,14.71) = 6.01, p = 0.018, η_p^2= 0.376), although post-hoc analyses did not reveal which conditions differed. There was no statistically significant limb by condition interaction effect (F(3, 30) = 1.15, p = 0.35, η_p^2 = 0.10) for BW MOS. In terms of ML MOS there were no significant limb (F(1, 10) = 0.91, p = 0.362, η_p^2 = 0.084), condition

(F(3,30) = 1.32, p = 0.285, η_p^2 = 0.117) nor interaction effects (F(1.64, 16.84) = 0.76, p = 0.46, =η_p^2 0.07) (Figure 2b).

Insert Figure 2 here

For all conditions, the step length was significantly larger for PROS limb relative to NONPROS limb, resulting in a significant limb main effect (F(1,10) = 9.14, p = 0.013, η_p^2 = 0.477). A statistically significant condition main effect for step length (F(1.24, 12.42) = 6.40, p = 0.021, η_p^2= 0.390) revealed shorter steps lengths in the NORM conditions vs. all other conditions (p < 0.05) (Figure 3a). The step length data did not result in a significant interaction effect (F(3, 30) = 0.60, p = 0.62, = η_p^2= 0.06). For all conditions, the step frequency did not vary between limbs, reflected in a non-significant limb effect (F(1, 10) = 0.53, p = 0.48, η_p^2= 0.05) (Figure 3b). However, step frequency resulted in a significant condition main effect (F(1.74, 17.37) = 4.58, p = 0.029, η_p^2= 0.314) although post-hoc tests did not indicate where this difference arose. Step frequency did not result in significant limb (F(1, 10) = 0.53, p = 0.48, η_p^2= 0.05) nor interaction effects (F(1.76, 17.56) = 1.15, p = 0.33, η_p^2= 0.10). There was no statistically significant condition effect in walking speed (F(1.71, 17.10) = 3.78, p = 0.05, η_p^2 = 0.27) (Figure 3c) and furthermore step width did not vary between conditions (F(3,30) = 0.81, p = 0.499, η_p^2 = 0.08) (Figure 3d).

Insert Figure 3 here

On average, both BW MoS (Table 2) and ML MoS (Table 3) decrease in the SYM_{SL} condition and increase in the SYM_{SF} condition for both limbs. In the $\text{SYM}_{\text{SL+SF}}$ condition, BW MoS remains stable on the NONPROS limb but shows a slight decrease on the PROS limb, for ML MoS it decreases on both limbs. It is important to note that individual variations exist, as indicated in Tables 2 and 3.

Insert Table 2 here

Insert Table 3 here

The analysis of step length (Table 4) reveals an overall increase in step length for both the PROS and NONPROS limbs across the different conditions but the inter-limb difference decreases. On the other hand, the analysis of step frequency (Table 5) demonstrates that step frequency varies depending on the condition, with either an increase or decrease observed on each limb. However, it is worth noting that there is a decrease in step frequency decreases between the limbs regardless of the condition.

Insert Table 4 here

Insert Table 5 here

The anaysis of speed (Table 6) shows a decrease in $\mathrm{SYM}_{\mathrm{SL}}$ condition but increase in $\mathrm{SYM}_{\mathrm{SF}}$ and $\mathrm{SYM}_{\mathrm{SL+SF}}$ but results differ between individuals and step width (Table 7) reveals that the average does not change between conditions.

Insert Table 6 here

Insert Table 7 here

Neither the correlation nor covariance PCA approaches revealed any clustering by condition but instead clustered more generally by participant and their limbs. This indicated a dominance of between-participant and between-limb variations, rather than between condition variation. The difference between PROS and NONPROS, shown in the previous statistical results, were highlighted in the PCA outcome by the solid and open circles which form clearly separated clusters, which is most evident by examining the second PC scores horizontally of both PCA approaches (Figure 4).

By examining the PC weightings of the eigenvalues (Figure 5), it is apparent that for the covariance approach the predominant second PC weightings relate to the vertical GRF (variable 3), sagittal knee joint angle (variable 17) and ankle joint angle (variable 20) (Figure 5a), i.e. they exhibit the largest deviations between the PROS and NONPROS limbs. The correlation approach reveals that knee joint angle (variable 17), ankle joint angle (variable 20) and knee joint moment (variable 16) have the greatest weighting and therefore exhibit the largest deviations between limbs (Figure 5b).

Insert Figure 4 here

Insert Figure 5 here

Discussion

The primary aim of this study was to identify the effects of attempting temporal-spatial symmetry on the dynamic stability of people with UTA. Despite the attempts of acute symmetry, people with LLA still walked asymmetrically. The results support the notion that asymmetrical gait in LLAs may be an important compensatory mechanism for the maintenance of stability. Furthermore, the absolute level of asymmetry in temporal-spatial parameters in these high-functioning individuals is relatively low. Based on the mean results, it appears that there may have been a decrease in BW MoS and ML MoS during attempted SYM_{SL}, suggesting a potentially less stable gait. Conversely, during attempted SYM_{SF}, there may have been an increase in BW MoS and ML MoS, indicating a potential improvement in gait stability. However, it is important to note that these results were not found to be statistically significant. Furthermore, during attempted SYM_{SL+SF}, it was observed that BW MoS remained stable on the NONPROS limb but exhibited a slight decrease on the PROS limb, implying less stability on the prosthetic limb. Additionally, ML MoS decreased even further compared to attempted SYM_{SL}, indicating a greater decrease in gait stability.

Backward MoS can be increased by an increase in step frequency or a decrease in step length, thus decreasing backwards loss of stability (Espy, Yang and Pai, 2010) which was also demonstrated in this study. The increased BW MoS during attempted SYM_{SF} implies that the extrapolated CoM can pass the posterior border of the BoS during the single support phase defined by the new stance limb, which decreases the risk of backward loss of stability (Hak *et al.*, 2014).

In response to perturbations, people with LLA have shown to increase step width probably as a control mechanism to allow them to increase ML MoS (Hak, van Dieën, *et al.*, 2013). Hof et al. (2007) state that ML MoS increases because of increased step width and frequency, where step frequency coincides with an increase in walking speed. However, in the current study, during attempted SYM_{SF}, the step frequency increased but the step width remained constant. Consequently, this explains why no change was observed in ML MoS, which might imply that step frequency and step length are predominantly associated with forward progression and BW MoS.

Attempting SYM_{SL} caused the step length to increase on both intact and prosthetic limbs. Although asymmetry seems reduced, the BW MoS and ML MoS showed a decrease during this condition, suggesting a potential compromise in dynamic stability. Speed also reduced during SYM_{SL} which is known to happen when individuals with LLA try to maintain dynamic stability (Hak *et al.*, 2013). Previous findings by Hak et al., (2012, 2013) revealed that in response to perturbations, LLAs decreased step length to maintain stability, rather than increase it, which is a compensation mechanism for the lack of CoM velocity resulting from reduced ankle push-off capacity on the prosthetic limb. Therefore, the attempt of SYM_{SL} in this study may have caused a reduction of this compensatory mechanism.

The secondary aim of this study was to identify and understand any biomechanical adaptations to gait during attempted temporal-spatial symmetry. In the assessment of kinetic and kinematic variables using PCA, the outcomes suggested that asymmetry still exits during attempted symmetrical conditions. The absence of significant results in the temporal-spatial parameters is supported by the lack of clustering by condition in the kinetic and kinematic variables. Instead, clustering occurred by limbs and by individuals. Clustering by limbs indicates a natural difference in the biomechanical parameters of the prosthetic and non-prosthetic leg. The differences between the limbs were attributed to the variability in vertical GRF, knee joint angle and ankle joint angle by the covariance approach, and due to the magnitude of the knee angle, the ankle joint angle and the knee joint moment by the correlation approach. Both PCAs indicate that the knee joint angle is the main causal factor differentiating between the prosthetic and intact limb, followed by the ankle joint angle. Previous research has predominantly focussed on the rigidity of the prosthetic ankle joint relative to a biological ankle joint. However, the current study has further identified the importance of the knee joint between the limbs. Clustering by individual is a strong indicator of the unique participant-specific gait characteristics and indicates the importance of patient-specific analysis. Future studies should focus on patient-specific characteristics as this could aid more informed decisions to be made with regards to prosthetic devices and rehabilitation programs. In future studies, machine learning algorithm such as linear discriminant analysis could be used to try and discriminate between conditions even if they are not statistically significant to identify what compensatory mechanics are adopted or being compromised when symmetrical gait is promoted. However, it may still be challenging when the uniqueness of participant gait is such a strong differentiator.

It is essential to interpret these findings cautiously due to the lack of statistical significance. Further analysis and investigation are necessary to determine the true impact and significance of these observations on overall gait stability. Based on a priori power analysis, it was estimated that a minimum of 15 participants across four repeated measures would be necessary to effectively investigate the impact of symmetry manipulations on walking gait in lower limb amputees and its effects on measures of dynamic stability. However, it should be acknowledged that the study fell short of reaching this desired number of participants, which may have resulted in underpowered statistical outcomes. Consequently, this limitation should be taken into consideration when interpreting the study's findings.

The objective of the study was to investigate the functional role of asymmetrical gait in individuals with lower limb amputations (LLA), rather than striving for perfect symmetry. It is important to acknowledge that when individuals with LLA attempted to walk with more symmetry, their gait did exhibit increased symmetry to some extent. However, it is noteworthy that a certain level of asymmetry still persisted. Moreover, as individuals approached greater symmetry in some conditions, their overall stability decreased, suggesting that the existing asymmetry may serve a functional purpose in their gait patterns.

Conclusion

Attempting temporal-spatial symmetry in people with UTA did not result in symmetrical gait but rather asymmetry was still present and dynamic stability was maintained. This highlights the functional role of asymmetry in maintaining a stable gait. Between limb differences are a dominant feature in people with LLA, are highly participant-specific and pose a practical problem for any experimental approach to identifying condition-specific differences using both conventional statistical and principal component analyses.

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