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Frontal Plane Dynamic Margins of Stability in Individuals With and Without Transtibial Amputation Walking on a Loose Rock Surface

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Abstract

Uneven walking surfaces pose challenges to balance, especially in individuals with lower extremity amputation. The purpose of this study was to determine if lateral stability of persons with unilateral transtibial amputation (TTA) is compromised when walking on a loose rock surface. Thirteen TTA and 15 healthy controls walked over level ground and over a loose rock surface at four controlled speeds. Dependent measures, including medial-lateral center of mass (COM) motion, step width variability, lateral arm swing velocity, and mean and variability of the minimum margins of stability (MOS_{min}), were compared between subject groups and across conditions. TTA had greater average MOS_{min} than Control subjects ($p = 0.018$). TTA exhibited decreased MOS_{min} on their prosthetic limbs compared to their intact limbs ($p = 0.036$), while Control subjects did not exhibit side to side differences. Both groups increased MOS_{min} with increasing walking speed ($p = 0.001$). There was no difference in the average MOS_{min} between walking surfaces ($p = 0.724$). However, the variability of MOS_{min} was greater on the rocks compared to level ground. Both subject groups increased step width, step width variability, COM range of motion and peak COM velocity when walking on the rock surface. TTA exhibited greater variability of both step width and MOS_{min} , which suggests that they made larger step-to-step, corrective responses, more often, to achieve the same average result.

Keywords

gait; amputation; irregular surface; lateral stability; step width variability

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Conflict of Interest Statement:

The authors have no conflict of interest with this work.

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1. Introduction

Falls are common in individuals with lower-limb amputation, with more than half of individuals with unilateral lower-limb amputation falling each year [1, 2]. Environmental factors like uneven terrain contribute to instability [3] and increase the frequency of falling [4].

In particular, people with lower-limb amputation may have difficulty maintaining lateral stability during walking, as ankle control plays a dominant role in medial-lateral balance [5]. People with lower-limb amputation have limited ankle joint mobility on the prosthetic side, and they lack distal muscles and afferent feedback from their lower limb [6]. These deficits reduce their capacity to control center of pressure (CoP) position while standing on their prosthetic limb such that they must use predictive strategies while walking [6]. Individuals with lower limb amputation (LLA) are therefore assumed to be less stable than able bodied individuals and have greater difficulty walking across uneven surfaces. However, recent studies that have attempted to verify this assumption reported conflicting and sometimes counterintuitive results [3, 7, 8]. LLA were equally stable on uneven ground and level ground in one study [7], but exhibited *increased* stability on uneven ground in another [8]. Additionally, LLA were found to be equally stable [7], more unstable [3, 8], or more stable [3] than able-bodied controls, depending on what measure was used to quantify stability. Results for between-limb differences in LLA are likewise inconsistent and counterintuitive, suggesting increased stability on the prosthetic limb compared to intact limb [3] or no between-limb differences [7].

The discrepancies between studies may be due to differences in how ‘stability’ was quantified, differences in the complexity of the surfaces studied, differences in patients tested (vascular or traumatic), or the different adaptations different subjects used to walk on these surfaces. For instance, LLA walked slower than controls in one study [8], but not in another [7]. Curtze et al. found that persons with transtibial amputation (TTA) adjusted their gait by increasing the maximum velocity of the lateral component of arm-swing when walking on an irregular surface, while unimpaired subjects did not [7]. They suggested arm swing played a vital role in TTA’s ability to maintain lateral balance by helping redirect the center of mass (COM) back over the base of support.

This study therefore quantified the lateral stability margins of young adults with and without traumatic transtibial amputations while walking over level ground and over a loose rock surface at four controlled speeds. Stability was quantified by calculating minimum medial-lateral margins of stability (MOS_{min}) during walking. We hypothesized that: 1) TTA exhibit smaller MOS_{min} (i.e., would be more unstable) than Control subjects, 2) Both subject groups would exhibit smaller MOS_{min} when walking on the rock surface compared to level ground, 3) Subjects’ MOS_{min} would become smaller when walking at faster walking speeds, and 4) TTA would exhibit smaller MOS_{min} on their prosthetic limb due to lack of active ankle control, while control subjects would not exhibit side to side differences in MOS_{min} . Additionally, we measured the medial-lateral movement of the whole body center of mass (COM), step width, step width variability, and lateral velocity of arm swing to determine what, if any, specific adaptations subjects made to maintain their medial-lateral balance.

2. Methods

2.1 Subjects

Thirteen young adults (12 male, 1 female) with traumatic unilateral transtibial amputation participated. Their average age, height, leg length, and body mass were 28 ± 4 years, 1.81 ± 0.09 m, 0.93 ± 0.05 m and 88.6 ± 14.4 kg, respectively. All participants were screened to

ensure they were free of orthopedic and neurological disorders to the intact side. Fifteen healthy young adults (12 male, 3 female) with a mean age of 22 ± 5 years, height of 1.71 ± 0.09 m, leg length of 0.89 ± 0.07 m and weight of 76.6 ± 11.6 kg also participated. All subjects provided written informed consent prior to participation.

2.2 Experimental Protocol

Kinematic data from 55 reflective markers were used to track full body kinematics at 120 Hz (Motion Analysis, Santa Rosa, CA) [9] while subjects walked over level ground and a loose rock surface (Figure 1A–B). Walking speeds were non-dimensionally scaled to leg length, l , according to $Speed = \sqrt{Fn \cdot g \cdot l}$, where Fn is the Froude number, and g is the gravitational constant [10]. Subjects walked at speeds corresponding to Fn of 0.06, 0.10, 0.16, and 0.23. A total of five left and five right strides with full kinematic data were analyzed for each speed, on each surface. One subject with TTA did not complete the fastest speed on the rock surface due to apprehension. All subjects wore their own athletic shoes during data collection.

2.3 Data Analysis

Kinematic and temporal spatial data were previously reported [11, 12]. Whole body center of mass (COM) was calculated as the weighted average of segment COMs based on anthropometric data [13]. Heel strikes were determined using a velocity-based detection algorithm [14] and verified by visual inspection. Step width was calculated based on the position of the heel markers at heel strike (Figure 1C).

Each subject's dynamic stability was determined via a technique based on the inverted pendulum model of balance [15]. According to this theory, a person is dynamically stable when their extrapolated center of mass (XcoM) lies within the border of their base of support (BOS). XcoM was calculated as:

$$X_{coM} = COM_z + \frac{C \dot{O} M_z}{\omega_o} \quad (1)$$

Where COM_z and \dot{COM}_z were the position and velocity of the COM in the medial-lateral direction, and ω_o was the eigenfrequency of a non-inverted pendulum with a pendulum length of 1.34 times trochanteric height [15]. At each instant in time, XcoM was used to define a margin of stability (MOS), proportional to the impulse needed to unbalance a subject, $MOS = BOS - X_{coM}$ [15]. Without center of pressure data, the lateral boundary of the BOS was estimated from the position of the 5th metatarsal marker (Fig. 1D). MOS_{min} was calculated as the minimum value of MOS during the stance phase. Within-subject variability of step width and MOS_{min} were calculated as the standard deviation across all five cycles collected for each condition.

Upon visual inspection of the data, it was evident that subjects were not walking straight relative to the laboratory coordinate system. To look specifically at deviations away from the path of progression, we performed a rotation on the foot marker data and center of mass motion [16].

The COM of each arm was determined from the weighted averages of the COMs of the upper arm, lower arm, and hand. Lateral arm swing velocity was defined as the movement of the arm COM in the medial-lateral (z) direction with respect to the shoulder such that a positive value indicated movement of the arm toward the stance limb (i.e., for a right gait cycle, arm movement to the right was positive) (See Supplemental Material for additional

details). For the arm swing velocity to effectively redirect the whole body COM, the peak velocity must occur prior to the change COM shift (ie. when COM velocity = 0). Thus peak lateral arm swing velocity was the maximum velocity achieved between 10% gait cycle and the time of COM shift (~ 35% gait cycle; Fig. 4, Supplemental Material).

2.4 Statistics

Subject demographics (age, height, and weight) between control and amputee groups were compared using t-tests. Dependent measures were first compared using mixed design repeated measures ANOVAs with walking surface (Rock/Level), walking speed (1–4), and limb (TTA: prosthetic/intact, Control: right/left) as within-subjects factors and subject group (TTA/Control) as a between subject factor. Repeated measures ANOVAs were then performed on each group separately where there were significant main effects or interactions with 'Group'. Height and weight were initially included as potential covariates. However, since neither was significant for any comparison, they were subsequently dropped. Statistical analyses were performed using SPSS v19 (SPSS Inc., Chicago, IL).

3. Results

TTA were, on average, 6 yrs older ($p = 0.001$), 9 cm taller ($p = 0.012$), and 11.1 kg heavier ($p = 0.029$) than control subjects. The two groups had similar leg lengths ($p = 0.22$), and thus walked at similar dimensionless speeds (Supplemental Material).

TTA exhibited a greater average MOS_{min} than control subjects ($p_{Group} = 0.018$; Fig. 2A). MOS_{min} increased with walking speed ($p_{Spd} < 0.001$), but was not sensitive to differences in walking surface ($p_{Sur} = 0.724$). TTA exhibited smaller MOS_{min} on their prosthetic limb compared to intact limb ($p_{Limb} = 0.036$), while Controls exhibited no significant between-limb differences ($p_{Limb} = 0.070$; $p_{Group \times Limb} = 0.018$). For TTA, the difference between the limbs decreased with increasing walking speed ($p_{Spd \times Limb} = 0.021$).

There were no between-group differences in variability of MOS_{min} ($p_{Group} = 0.907$; Fig. 2B). There was a significant overall main effect for walking speed ($p_{Spd} = 0.011$). Analyzing the groups separately, the decrease in MOS_{min} variability with increasing walking speed was significant in TTA ($p_{Spd} = 0.027$) but not Control ($p_{Spd} = 0.545$) subjects. For both groups, MOS_{min} variability was greater on the rock surface than level ground ($p_{Sur} < 0.001$).

There were no between-group differences in average step width ($p_{Group} = 0.222$; Fig. 3A). TTA exhibited greater step width variability than control subjects ($p_{Group} < 0.001$; Fig. 3B). Both groups increased step width ($p_{Sur} = 0.017$) and step width variability ($p_{Sur} < 0.001$) on the rock surface compared to level ground. TTA exhibited a greater difference in step width variability between walking surfaces than Control subjects ($p_{Group \times Surface} = 0.014$; Fig. 3B). TTA also had greater step width variability when stepping onto their intact limb ($p_{Limb} = 0.001$). Control subjects exhibited no between-limb differences ($p_{Limb} = 1.0$; $p_{Group \times Limb} < 0.001$).

At initial contact, TTA exhibited a greater distance between the lateral border of their base of support (BOS) and their COM than Controls ($p_{Group} = 0.008$; Fig 4A). There was a greater distance between the COM and BOS when TTA stepped on their intact limb, than their prosthetic limb ($p_{Limb} < 0.001$). Both groups showed a significant decrease in distance between their COM and BOS with increased walking speed ($p_{Spd} < 0.001$). There were no differences between walking surfaces ($p_{Sur} = 0.137$) or between limbs of control subjects ($p_{Limb} = 0.178$).

TTA displayed increased medial-lateral center of mass motion (COM_{M-L}) during stance compared to Control subjects (Fig. 4B; $p_{Group} < 0.001$). COM motion decreased with increasing walking speed for both groups ($p_{Spd} < 0.001$). There were significant Group \times Limb ($p = 0.002$) and Group \times Speed ($p < 0.001$) interactions. At the slower speeds, TTA had increased COM motion on their prosthetic limb compared to their intact limb ($p_{Limb} = 0.019$, $p_{Limb \times Spd} = 0.023$). There was no effect of walking surface on COM motion in either group ($p_{Sur} > 0.165$).

Peak COM velocity was greater in TTA than Control subjects (Fig 4C; $p_{Group} = 0.006$). Control subjects had greater peak velocity on the rock surface compared to level ground ($p_{Sur} = 0.005$), while TTA did not ($p_{Sur} = 0.323$). Peak COM velocity decreased with increasing walking speed for both groups ($p_{Spd} < 0.001$). This decrease was greater on the rock surface than the level surface for TTA ($p_{Spd \times Sur} = 0.003$).

Both the magnitude and timing of peak lateral arm swing velocity were highly variable across subjects (Fig. 5). In many trials there was no clear velocity peak. The maximum lateral arm swing velocity prior to redirection of the COM was not different between TTA and control subjects for either the ipsilateral ($p_{Group} = 0.766$) or contralateral ($p_{Group} = 0.574$) arms. There were no main effects for surface ($p_{Sur} > 0.135$) or limb ($p_{Limb} > 0.075$) and no significant interactions with 'Group.'

4. Discussion

This study compared medial-lateral center of mass control in persons with unilateral transtibial amputations (TTA) and able-bodied control subjects. We tested four hypotheses, only one of which was supported. Contrary to expectations, TTA exhibited greater margins of stability than able-bodied control subjects (Fig. 2A), indicating they were laterally more stable despite their lack of active ankle control. Both groups were also laterally more stable when walking at faster speeds, but equally stable on the different surfaces. The one hypothesis that was supported was that TTA exhibited smaller MOS_{min} (i.e., decreased stability) on their prosthetic limbs, while control subjects did not exhibit side-to-side differences in lateral stability.

4.1 Comparison across speeds

At the faster walking speeds, both groups exhibited decreased COM-to-BOS distance (Fig. 4A), medial-lateral COM range of motion (Fig. 4B), and peak COM velocity (Fig. 4C). When combined, these changes lead to increased mean medial-lateral MOS_{min} in both groups when they walked at faster speeds (Fig. 2A). Additionally, TTA also decreased variability (SD) of their medial-lateral MOS_{min} (Fig. 2B). The changes in medial-lateral COM range of motion (Fig. 4B) were consistent with previous work [17]. Hof et al. [18] also reported a trend (although not significant) toward increased medial-lateral MOS_{min} at faster walking speeds. While these findings suggest these subjects were *laterally* more stable at faster speeds, this does not necessarily imply they were "safer" in terms of risk of falling in general. Indeed, in the elderly, although slower walking speeds increase the risk of indoor falls, *faster* walking speeds increase the risk of *outdoor* falls [19–21], where irregular terrains abound. Elderly subjects who walk faster are also more likely to trip and fall [22], primarily due to the need for much faster response times [23]. The increase medial-lateral MOS_{min} observed at faster walking speeds here are more likely an adaptation these subjects adopt to mitigate any increased risk of falling, similar to the way the TTA also exhibited larger medial-lateral MOS_{min} than Controls (Fig. 2A), in spite of the fact that these patients have a higher risk of falling [1–4].

4.2 Comparison between surfaces

Mean MOS_{min} were not different between surfaces for either group (Fig. 2). This result, while seemingly counterintuitive, agrees with previous work in healthy individuals walking on irregular and compliant surfaces [7, 24], and TTA walking on an irregular surface [7]. There are several possible reasons for these results. First, the different surfaces used may not be difficult enough to challenge balance in these patients. This seems unlikely, however, especially as the loose rocks were not only irregular, but they also slide and/or sink underneath the feet. This likely requires subjects to make active adjustments to control lateral CoP position.

Another possibility is that subjects adapted their walking patterns to maintain a constant MOS_{min} in spite of any challenge surface provides. TTA increased their average step width and step width variability (Figs. 3A & 3B). Control subjects increased their COM velocity (Fig. 4C) and step width variability (Fig 3C). Neither the TTA nor Control subjects increased their peak arm swing velocity, however. Due to relative timing differences, arm swing velocity is not likely to be employed as a strategy to minimize the MOS. The minimum MOS typically occurred around 10% of the gait cycle, far sooner than any movement of the COM.

Finally, the *average* MOS_{min} may not be the most appropriate or sensitive measure of subtle challenges in walking stability. The goal during walking may not be to maximize MOS_{min} , but rather to maintain a sufficient MOS_{min} as to not lose balance. In this sense, the variability of MOS_{min} may reveal how well controlled this parameter is under the different conditions. Variability of MOS_{min} was greater when walking on the rock surface in both subject groups. Similarly, healthy individuals had similar average MOS_{min} but greater variability when walking on compliant foam compared to level ground [24]. Another possibility is that individuals do not attempt to control either the mean or variability of MOS_{min} , but rather how quickly they can correct a negative MOS_{min} [25]. The current experimental set-up did not allow us to quantify this since we could only record a few consecutive steps on each pass through the rock surface.

4.3 Comparison between limbs

Controls did not exhibit any side-to-side differences. TTA, on the other hand, exhibited differences between their intact and prosthetic limb for several dependent measures (Figs. 2–5). TTA had greater step width variability when stepping onto their intact limb. They also had greater COM range of motion when standing on their prosthetic limb, perhaps due to an inability to stabilize the CoP under the foot without ankle muscle control. Additionally, when TTA stepped onto their prosthetic limb, there was a reduced distance between the lateral border of the BOS and the COM. This likely contributed to the reduced MOS_{min} on their prosthetic compared to their intact limb, as it would require them to increase their COM velocity on the intact side to maintain similar MOS_{min} on both limbs.

4.4 Limitations

The TTA studied here were otherwise healthy and very active. Therefore, these results may not extrapolate all populations of TTA. Additionally, it was not possible to measure center of pressure when subjects walked on the rock surface. We therefore used the position of the 5th metatarsal marker to estimate the lateral border of the base of support on both surfaces. It is possible the subject groups differed in how their CoP moved underneath the foot during stance. For instance, Hof et al. [18] found that patients with transfemoral amputations were able to move their CoP away from the XcoM during stance, when standing on their intact limb, but not on their prosthetic side. With the current experimental paradigm, such differences were not detectable.

5. Conclusion

Patients with transtibial amputations and healthy control subjects altered their gait when walking on a rock surface by increasing their base of support and altering their foot placement. Both subject groups thus maintained similar average lateral MOS_{min} on level ground and a more challenging loose rock surface. Patients with transtibial amputations made different adjustments on their intact and prosthetic sides. Despite adjusting foot position and center of mass movement, they had decreased lateral MOS_{min} on their prosthetic side compared to their intact limb. TTA had greater average MOS_{min} than healthy controls. TTA did exhibit greater variability of both step width and MOS_{min} , which suggests they made larger step-to-step corrective responses, more often, to achieve the same average result.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Research Highlights

1. Uneven walking surfaces disrupt balance in those with lower extremity amputation.
2. Patients with unilateral transtibial amputations walked on a loose rock surface.
3. Both patients and controls increased base of support and altered foot placement.
4. Both groups maintained similar lateral margins of stability on both surfaces.
5. Patients made larger step corrections, more often, to maintain lateral stability.

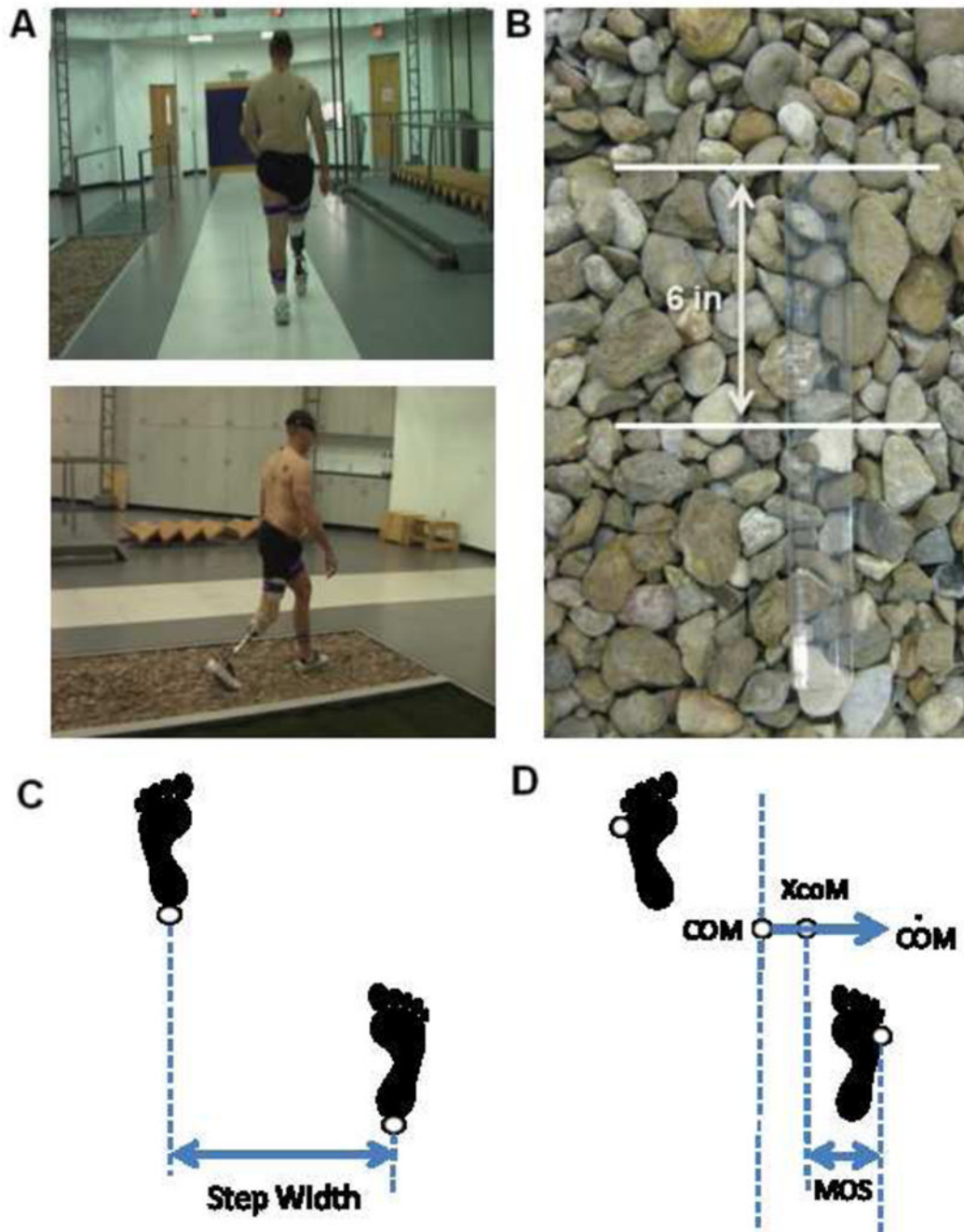


Figure 1. Experimental Set-up

A) Subjects walked at four speeds across both level ground (top) and a rock surface (bottom). The rock surface was a 4.2-m long by 1.2-m wide pit filled with loose rocks. B) A close-up of the rocks surfaces is shown with a ruler to provide dimension. C) Step width was calculated as the medial-lateral distance between the heel markers at heel strike. D) The margin of stability (MOS) was the medial-lateral distance between the lateral border of the base of support (BOS), defined by the 5th metatarsal marker, and the vertical projection of the extrapolated center of mass (XcoM).

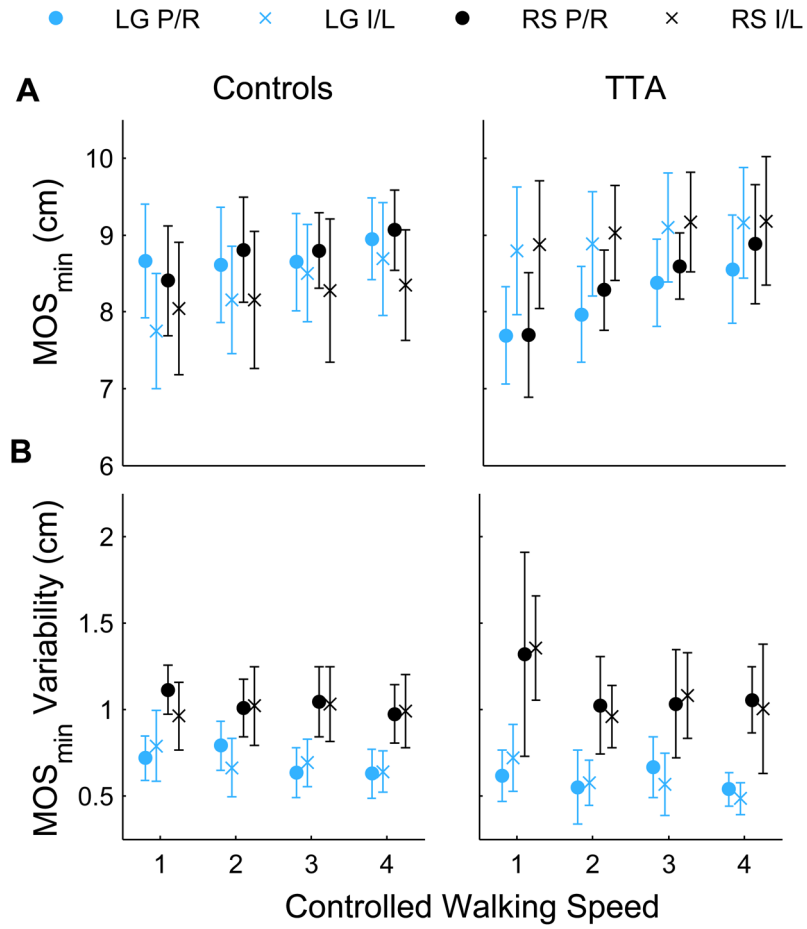


Figure 2. Margin of Stability

Minimum margins of stability, MOS_{min} , and the within subject variability of MOS_{min} are shown for the control and TTA subjects. Data is shown for the rock surface ('RS') and level ground ('LG') at each of the four controlled walking speeds (shown from slowest to fastest). 'x' represent the right leg for the controls and the intact limb for the amputees. '•' represent the left side for the controls and prosthetic limb for the amputees. Error bars represent $\pm 95\%$ confidence intervals about the mean.

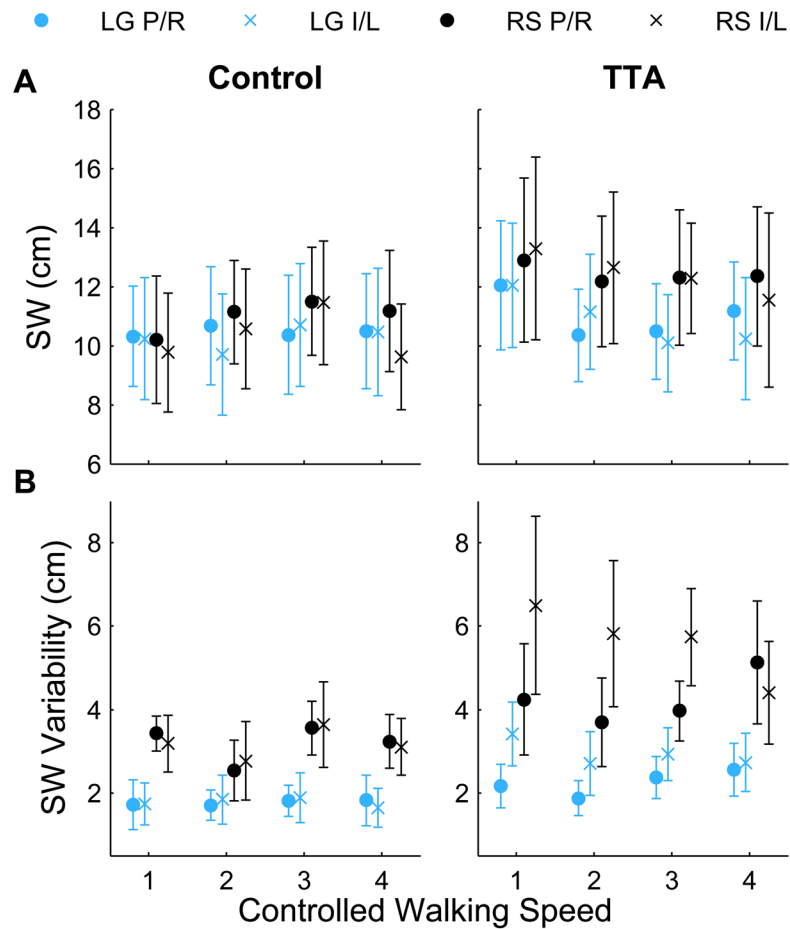


Figure 3. Step Width Mean and Variability

The average and within-subject variability of step width (SW) are shown for the control subjects and subjects with transtibial amputations (TTA). For TTA subjects, this was the prosthetic ('P') and intact ('I'), while for controls this was right ('R') and left ('L'). Subjects walked across a rock surface (RS; 'x') and over level ground (LG; '•') at four controlled speeds (shown from slowest to fastest). Error bars represent $\pm 95\%$ confidence intervals about the mean.

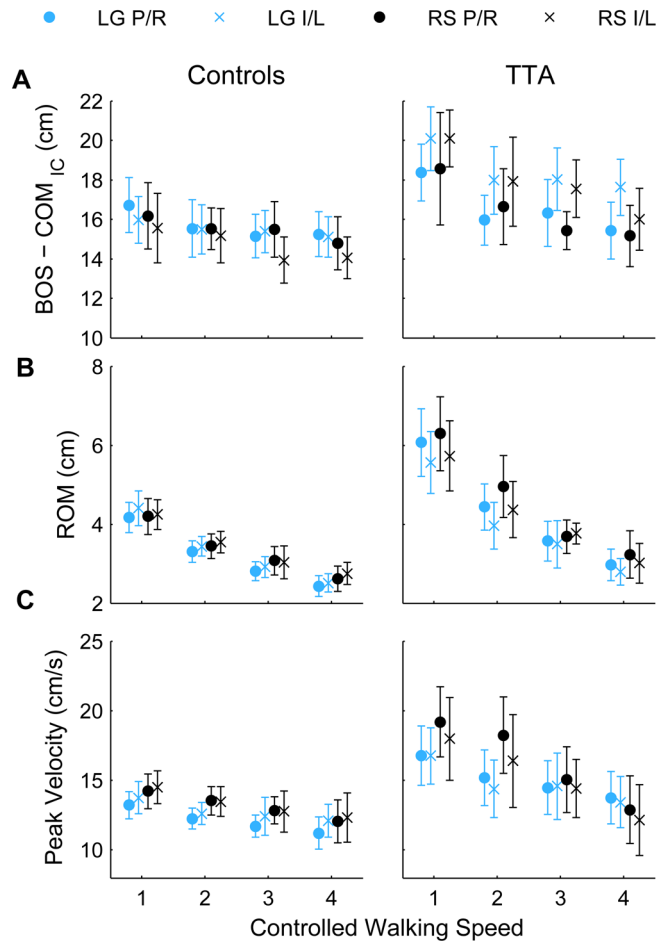


Figure 4. Medial-Lateral Center of Mass (COM) Motion

A) The distance between the COM and base of support at initial contact, B) COM range of motion (ROM) during stance, and C) The peak velocity of COM during stance are shown for the rock surface (RS) and level ground (LG) at each of the four controlled walking speeds (shown from slowest to fastest). Average trajectories were computed for each subject across five walking trials for the prosthetic ('P') and intact ('I') limbs for patients with transtibial amputations (TTA) and right ('R') and left ('L') limbs for control subjects. Errorbars represent the 95% confidence intervals about the mean, across subjects.

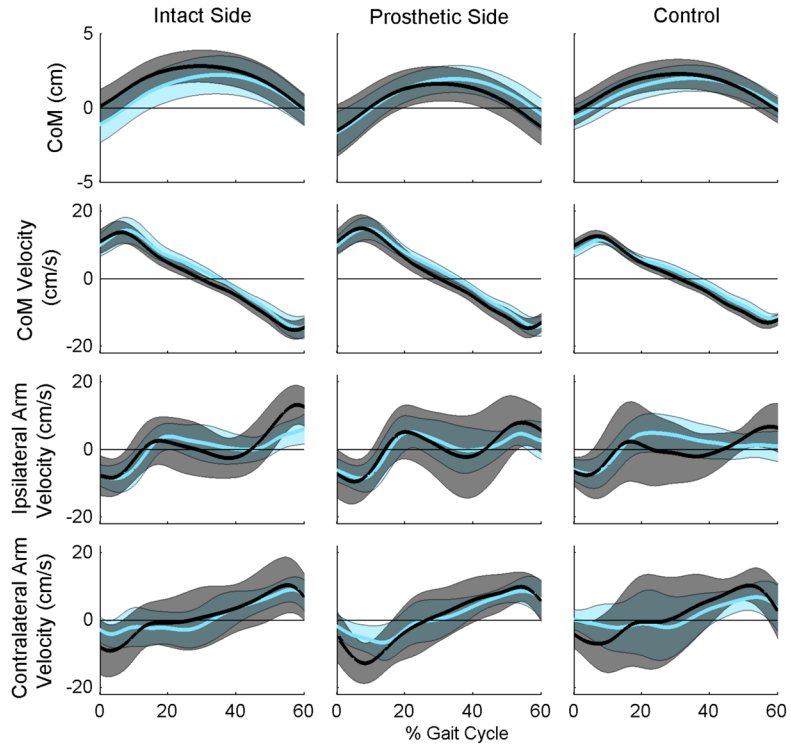


Figure 5. Center of Mass Movement and Arm Swing Velocity
Lines represent the average behavior across subjects during walking overground (cyan) and on the rock surface (black) at controlled speed 3. Bands represent the standard deviation across subjects. Control data is shown for the right side only. Positive values are toward the stance limb, (Left) Intact, (Middle) Prosthetic, and (Right) Right limb of control subjects.