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Kinematic Strategies for Walking Across a Destabilizing Rock Surface☆

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Abstract

It is important to understand how people adapt their gait when walking in real-world conditions with variable surface characteristics. This study quantified lower-extremity joint kinematics, estimated whole body center of mass height (COM_{VT}), and minimum toe clearance (MTC) while fifteen healthy, young subjects walked on level ground (LG) and a destabilizing loose rock surface (RS) at four controlled speeds. There were no significant differences in average step parameters (length, time, or width) between the walking surfaces. However, the variability of these parameters increased twofold on the RS compared to LG. When walking on the RS, subjects contacted the surface with a flatter foot and increased knee and hip flexion, which enabled them to lower COM_{VT}. Subjects exhibited increased hip and knee flexion and ankle dorsiflexion during swing on the RS. These changes contributed to a 3.8 times greater MTC on the RS compared to LG. Peak hip and knee flexion during early stance and swing increased with walking speed, contributing to decreased COM_{VT} and increased MTC. Overall, subjects systematically adapted their movement kinematics to overcome the challenge imposed by the destabilizing loose rock surface.

Keywords

Irregular or Uneven terrain; Walking Surfaces; Kinematics; Variability; Gait

1. Introduction

In daily life, people walk over a variety of terrains with different surface characteristics. These include compliant surfaces like grass or sand, slippery surfaces like puddles or ice, and uneven ground like rocks or curbs. Few studies have directly compared walking under such real-world conditions to walking on level ground or treadmills [1]. However, most falls

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occur outdoors and are caused by environmental factors like uneven surfaces [2, 3]. Thus, determining how people walk on such surfaces is critical as these surfaces apply both mechanical and kinesthetic perturbations [4], which could result in falls if individuals do not or cannot adapt their gait appropriately.

Studies which did quantify changes in gait in response to challenging walking surfaces [2, 3, 5–10] tested randomly-placed objects hidden beneath a carpet or artificial grass [5, 7–9], compliant foam [2, 3], or tiles oriented at different angles [10]. Individuals consistently adapted their walking strategy to effectively negotiate these walking surfaces. For example, individuals increased toe clearance to prevent tripping over an irregular surface [9, 11]. Healthy, young adults also lowered their center of mass (COM) when stepping onto a compliant surface [2, 3] and when walking on a slippery surface [12]. A lower COM may enhance stability by decreasing the moment arm between the COM and the ground reaction force, such that a greater amount of force is needed to induce a fall [2]. In some cases, young adults decreased their walking speed in response to the added challenge [9], while in others, they did not [6, 14]. When walking over potentially slippery surfaces, subjects took shorter steps and exhibited a flatter shoe-floor angle at heel strike [9, 12].

Previous work on challenging walking surfaces primarily quantified changes in temporal-spatial parameters (e.g. step length and time) while individuals walked at a self-selected pace [6, 7, 9]. However, because walking speeds were generally slower for uneven terrains [9, 10], changes in step parameters may have reflected changes in speed more than any differences in movement strategies [15]. To date, no studies have examined what kinematic adaptations healthy adults make to successfully negotiate uneven terrain at controlled walking speeds.

This study quantified lower limb joint kinematics and COM motion while subjects walked across level ground (LG) and on a destabilizing loose rock surface (RS) at four controlled speeds. We expected the RS would be especially challenging as it is simultaneously uneven, unpredictable, and moveable. The loose rocks could cause a trip if subjects did not maintain appropriate toe clearance. Subjects could also slip or slide on the rocks if they did not adapt to the rocks moving underneath the foot. We hypothesized that individuals would significantly alter their joint kinematics when walking on the RS, compared to LG, and that these adaptations would be more pronounced at faster speeds. Based on previous research involving different challenging surfaces, we hypothesized that subjects would reduce their shoe-floor angle at initial contact, increase their minimum toe clearance, and lower their COM when walking on the RS.

2. Methods

2.1 Subjects

Fifteen healthy, young adults (3 female, 12 male) participated. Their average age, height, and weight were 22 ± 5 years, 1.71 ± 0.09 m and 76.6 ± 11.6 kg, respectively. All subjects provided written informed consent prior to participation in this institutionally approved study.

2.2 Experimental Protocol

Subjects walked over level ground (LG) and over a destabilizing loose rock surface (RS) at four controlled speeds (Fig. 1). The LG was a 5 m level walkway. The RS consisted of a 4.2 m long by 1.2 m wide by 10 cm deep pit filled with loose river rocks. Each capture area was preceded by a 4.6 m level walkway which allowed subjects to reach steady speed prior to data collection [17]. Subjects were also instructed not to look down unless they “felt that they were about to lose their balance and fall.”

Walking speeds were normalized according to Froude Number to scale speed to each subject's leg length [18]. Subjects walked at Froude numbers of 0.06, 0.1, 0.16, and 0.23. Prior to collecting these set speeds, subjects were able to walk across the LG and RS at their self-selected speeds to acclimate to the task. These speeds were recorded, and the average of five trials was noted. The order of testing was randomized such that each speed was performed first on the LG and then on the RS. An audible cuing system provided real-time feedback of walking speed by generating a loud tone when the subject's speed was within the prescribed range (±5% target speed) (Biofeed Trak, Motion Analysis, Santa Rosa, CA). Only strides within 10% of each target speed were accepted. A total of five left and five right strides were collected for each subject walking at each speed on each surface.

2.3 Data Analysis

Kinematic data were collected at 120 Hz using a 20 camera infrared motion capture system (Motion Analysis, Santa Rosa, CA). 55 reflective markers were used to track whole body kinematics (See Supplemental Material for additional details). The locations of 20 bony landmarks in relation to marker clusters were found by manual palpation and recorded using a digitizing pointer (C-Motion, Inc., Germantown, MD). Kinematic data were filtered using a 4th order low-pass Butterworth filter with a 6 Hz cut-off frequency. Heel strikes were determined using a velocity-based detection algorithm [19] and then verified by visual inspection. Step time (ST) was the time between consecutive right and left heel strikes. Step length (SL) and step width (SW) were defined as the distance between the right and left heel markers at heel strike in the anterior-posterior and medial-lateral directions, respectively. The standard deviations of ST, SL, and SW computed across all five cycles collected for each limb for each condition represented within-subject variability. Foot angle at initial contact (θ_F) was defined as the angle between horizontal and a line connecting a marker placed on the heel and one placed on the base of the 1st metatarsal [9]. The position of the foot during a static trial (ie. neutral position) was subtracted from this angle for normalization. Minimum toe clearance (MTC), was the vertical distance between the first metatarsal marker at its lowest point in stance and its lowest point in mid-swing [9]. MTC at mid-swing indicates the potential risk of tripping [9, 20]. A lower or more variable MTC clearance would indicate a greater likelihood of tripping [9, 12].

Segmental markers and landmarks were used to create a 15 segment whole-body model in Visual3D (C-Motion, Inc., Germantown, MD). Local coordinate systems for each segment were defined using ISB recommendations [21, 22]. Segmental masses were assigned based on the anthropometric data of Dempster [23]. Whole body center of mass (COM) was calculated as the weighted average of each segment's COM. Vertical COM displacement (COM_{VT}) was normalized to each subjects' standing height for comparison across subjects. To ensure changes in COM height were not due merely to displacement of the rocks, the vertical height of the ankle joint center during stance was subtracted from COM_{VT} [4].

Angular motions of the ankle, knee, and hip were calculated using Euler angles. Joint angles and COM_{VT} were time normalized to 0 to 100% of the gait cycle. Variability was quantified as MeanSD: the average width of the standard deviation across the movement cycle [24].

A preliminary comparison of right and left sides revealed no significant side difference for any dependent measure. Therefore, right and left data were pooled and then averaged. Separate two-factor, within-subjects ANOVAs were used for each dependent measure to test for differences between walking surfaces (LG v RS) and walking speeds (speed 1–4) with a level of significance of $p \leq 0.05$ (SPSS 16, Chicago, IL). Significant interaction effects were explored using the Estimated Marginal Means with a Bonferroni correction.

3. Results

3.1 Temporal-Spatial Parameters

Subjects walked with a self-selected speed of 1.19 ± 0.15 m/s on the RS compared to a speed of 1.34 ± 0.16 m/s on LG. Given the subject anthropometrics, the four controlled speeds (speed 1 – 4) were approximately 0.71, 0.95, 1.19, and 1.42 m/s. Thus, the speed 3 best approximated the subject's self-selected speed on the RS, while Speed 4 best approximated their self-selected speed on LG.

When walking at faster speeds (Fig. 2A), subjects increased their SL ($p_{Spd} < 0.001$) and decreased their ST ($p_{Spd} < 0.001$), but maintained constant SW ($p_{Spd} = 0.634$). There were no differences in SL, ST, or SW between walking surfaces, nor any interaction effects. Mean (±SD) and p-values for all comparisons are provided as Supplemental Material.

3.2 Temporal-Spatial Variability

Overall, step variability (SL, ST, and SW) was greater on the RS than LG ($p_{Sur} < 0.001$; Fig. 2B). ST variability decreased with increasing speed ($p_{Spd} < 0.001$). There was a significant interaction effect for ST variability ($p_{Spd \times Sur} = 0.003$). For the LG, all speeds were ignificantly different except speeds 2 and 3. For the RS, only speed 1 was significantly different from all other speeds (speed 2–4). There was also a significant interaction effect for SL variability ($p_{Spd \times Sur} = 0.009$). Post-hoc analysis revealed that speeds 1 and 4 on the LG were significantly different.

3.3 Kinematics

Initial Contact—Subjects contacted the ground with a relatively flatter foot on the RS than the LG ($p_{Sur} < 0.001$; Fig 5A). Foot angles at heel strike were 11.3 ± 6.2° on RS, compared to 21.7 ± 5.7° on LG. Foot angles increased with increasing walking speed over both surfaces ($p_{Spd} < 0.001$).

Early Stance—Because the foot was nearly flat at heel strike, there was almost no ankle plantarflexion during early stance when walking over the RS (Fig. 3A–B). Peak plantarflexion angles were −1.1 ± 4.4° on the RS and s;5.2 ± 2.2° on the LG ($p_{Sur} = 0.001$). There was an 8° increase in knee flexion and a 6.9° increase in hip flexion when subjects walked on RS compared to LG ($p_{Sur} < 0.001$). Peak knee and hip flexion increased with walking speed ($p_{Spd} < 0.001$). Ankle plantarflexion was greater at speed 4 than speeds 1 and 2 on the RS ($p_{Spd} < 0.001$; $p_{Spd \times Sur} = 0.015$).

Late Stance—Subjects dorsiflexed their ankles quickly during midstance when walking over the RS, but still maintained similar dorsiflexion prior to toe-off compared to LG. While the differences at the ankle and hip were statistically significant (Fig 3C), they were <1° on average. Peak hip extension increased approximately 5° from the slowest to fastest speed ($p_{Spd} < 0.001$).

Swing—Subjects exhibited increased hip and knee flexion and ankle dorsiflexion during swing on the RS ($p_{Sur} < 0.001$; Fig. 3D). Peak hip flexion increased 11.1° from the LG to the RS while peak knee flexion increased 10.3°, and peak ankle dorsiflexion increased 5.2°. There were significant main effects for speed and speed × surface interactions for all comparisons ($p_{Spd} < 0.001$; $p_{Spd \times Sur} < 0.03$). For the hip and knee, this interaction signified that the increase in peak angle with speed were greater when subjects walked on RS than LG. At the ankle, there was no difference in peak dorsiflexion with speed on the RS while dorsiflexion decreased with speed on LG (speeds 2–4 were significantly different from speed 1). MTC was 3.8 times greater on the RS than LG ($p_{Sur} < 0.001$; Fig. 5B). There was a significant main effect for speed and interaction ($p_{Spd} < 0.001$; $p_{Spd×Sur} < 0.001$). MTC increased with speed on the RS only.

3.4 Kinematic Variability

The joint angle MeanSD at the ankle, knee, and hip were greater on the RS than the LG ($p_{Sur} < 0.001$; Fig. 4). There were no significant main effects for speed at any joint, but there were significant interactions for all comparisons ($p_{Spd×Sur} < 0.026$). Differences between the speeds were only present on the RS.

3.5 COM Motion

COM_{VT} was significantly lower on the RS ($p_{Sur} = 0.001$; Fig. 5C) and decreased with increasing speed ($p_{Spd} < 0.001$). COM_{VT} range of motion was greater on the RS ($p_{Sur} < 0.001$) and at faster speeds ($p_{Spd} < 0.001$). The changes in COM_{VT} position and range of motion with speed were greater on the RS ($p_{Spd×Sur} \leq 0.007$).

4. Discussion

The aim of this study was to quantify adaptations in lower extremity kinematics and center of mass motion that young, healthy individuals used to transverse a destabilizing rock surface. Not surprisingly, subjects in this study successfully negotiated the rock surface without slipping, tripping or falling. Subjects adapted to the rock surface by making preparatory adjustments to their posture prior to contact with the walking surface.

When speed was controlled, mean step parameters (length, time, width) did not differ between walking surface (Fig. 2A). Surface type did, however, affect variability of all step parameters and kinematic measures (Figs. 2B and 4). The increased variability of ST and SW were consistent with several previous studies of walking on irregular or compliant terrain [4, 6, 15]. Stride-to-stride variability correlates with increased fall risk [25, 26], and thus, may suggest that subjects were at a greater risk of falling when walking on the rock surface. However, inter-stride variability provides only an indirect measure of stability[15], and these measures do not reveal which specific kinematic adaptations individuals make to maintain balance. In the present study, the observed increased variability could also have occurred solely from the variable surface characteristics of the rocks. Similarly, in a passive dynamic walking model, increased variability of the walking surface lead to exponential increases in kinematic variability [27].

In general, the changes in temporal-spatial parameters with increasing walking speed were consistent with published data for level walking [28–30]. Trends with walking speed were only different between RS and LG for a few variability parameters. The variability of the joint angles, SL, and SW either increased with speed or did not change on the RS surface, while this variability decreased with speed when subjects walked over LG. These results will be helpful in future comparisons of temporal-spatial measures across walking surfaces when subjects are allowed to walk at self-selected speed.

There were significant kinematic differences between walking surfaces during the swing phase (Fig. 3A,D). These adjustments included increased hip and knee flexion and ankle dorsiflexion, which allowed subjects to increase their MTC (Fig. 5D). MTC was 3.8 times greater on the RS than LG. As MTC indicates the potential risk of tripping [7, 18], increased MTC likely reduced the subjects' tripping risk. This finding supports the work of several others [7, 10, 30]. Young adults exhibited a 2- to 3-fold increase in MTC when walking over surfaces with various sized obstacles (13 – 50 mm obstacles), compared to an obstacle-free surface [7, 10, 30] and when walking on a compliant surface [28]. MTC increased with walking speed on the RS but not on the LG (Fig. 5B). Schulz [10] found that MTC did not change between slow and preferred speeds, but increased from preferred to fast speeds for both level ground and obstacles. This finding is in line with the present work as the speeds used here were much slower than those used by [11], where their ‘preferred’ speed was equivalent to our fastest speed (speed 4). Although this was not part of our analysis, the variability of toe-clearance was also greater on the rock surface ($p_{Sur} < 0.001$). This was not unexpected, since the surface height was also more variable.

The increased flexion at terminal swing also enabled subjects to contact the rock surface with a flatter foot than during level walking (Fig. 5A). Subjects may have made these preparatory adjustments because they perceived that the rocks could slide under their shoes. Previous studies report shorter steps and flatter shoe-floor angles when subjects walk over a potentially slippery surface [9, 14, 32]. This adaptation reduced the risk of initiating a slip by lowering the required coefficient of friction at the shoe-floor interface [9, 14]. Increased flexion also contributed to decreasing COM_{VT} (Fig. 5C). This adaptation presumably mitigated the instability created by the rock surface. Similarly, healthy, young adults also lowered their center of mass (COM) when stepping onto other destabilizing surfaces, including compliant [4, 10] and slippery surfaces [13].

4.3 Limitations

As the rocks were loose, it was not possible to measure the actual height of the walking surface. COM_{VT} was measured with respect to the height of ankle joint center, which does move throughout stance, though the actual surface does not. Decreases in this derived COM height, combined with the changes in joint angle kinematics, do suggest that subjects actively lowered their COM. The inability to determine ground height also affected our calculations of MTC. In agreement with others [9], MTC was calculated with respect to the lowest toe height during stance. The foot could displace the surrounding rocks and sink into the surface. Thus, the height of the rocks, where the toe reached its minimum during swing, was likely not as low as the lowest toe height during stance. The increased overall flexion during swing, along with the large between-condition differences in MTC (5.5 cm), suggest that this difference would still be found if the height of the rocks could be determined.

5. Conclusion

When walking over a loose rock surface at various speeds, subjects altered their kinematics without changing their average step parameters. Increased lower extremity flexion during terminal swing and early stance helped to actively lower the COM position, presumably to enhance stability. Subjects also increased MTC on the RS to reduce their risk of tripping and lowered their shoe-floor angle at heel strike to decrease their risk of slipping or displacing the rocks. Overall, these healthy, young subjects adapted to the perturbations imposed by this destabilizing surface in specific ways to maintain balance and reduce their risks of falling.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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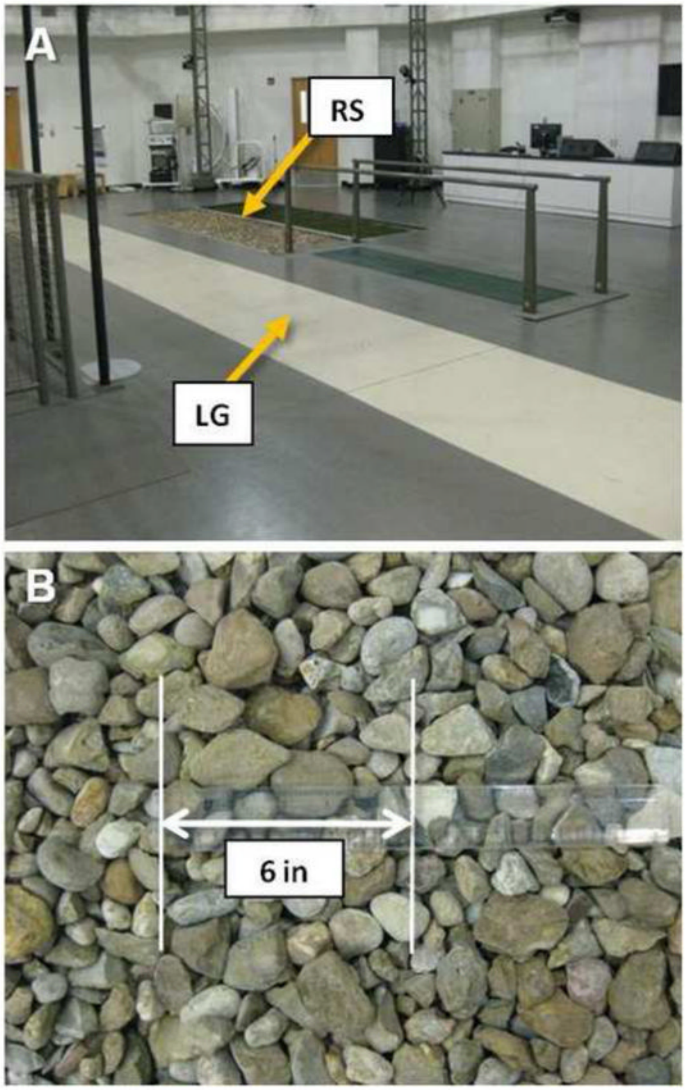

Figure 1.

Experimental Set-Up. A) Photograph depicting the laboratory in which testing was performed. Subjects walked on a level laboratory surface (LG) and over a destabilizing loose rock surface (RS). B) Photograph depicting the RS. A ruler is shown to provide scaling.

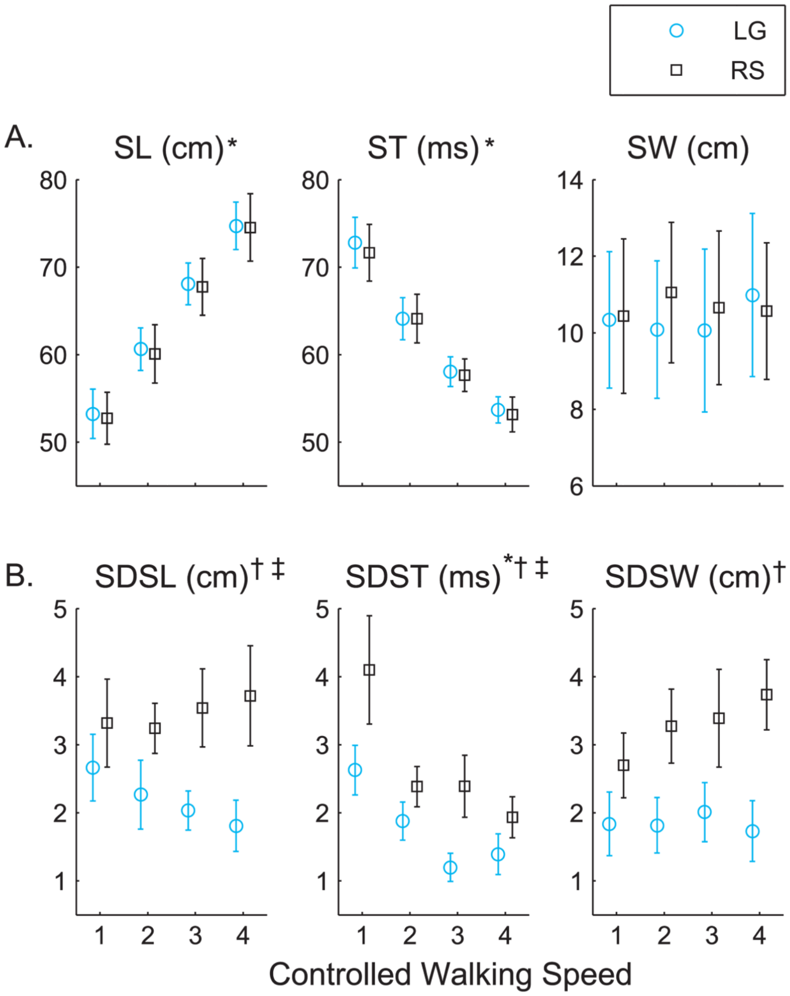

Figure 2.

Temporal Distance Parameters. Subjects walked across a destabilizing loose rock surface (RS; '☐') and over level ground (LG; 'O') at four speeds. A) The average step length (SL), step time (ST), and step width (SW) across subjects are shown for each condition. B) The average within-subject variability of SL, ST, and SW are shown for each condition. Error bars represent ± 95 % confidence intervals about the mean.

* Statistically significant main effects for walking speed ($p < 0.001$)

† Statistically significant main effects for walking surface ($p < 0.001$)

‡ Statistically significant speed × surface interactions ($p < 0.01$)

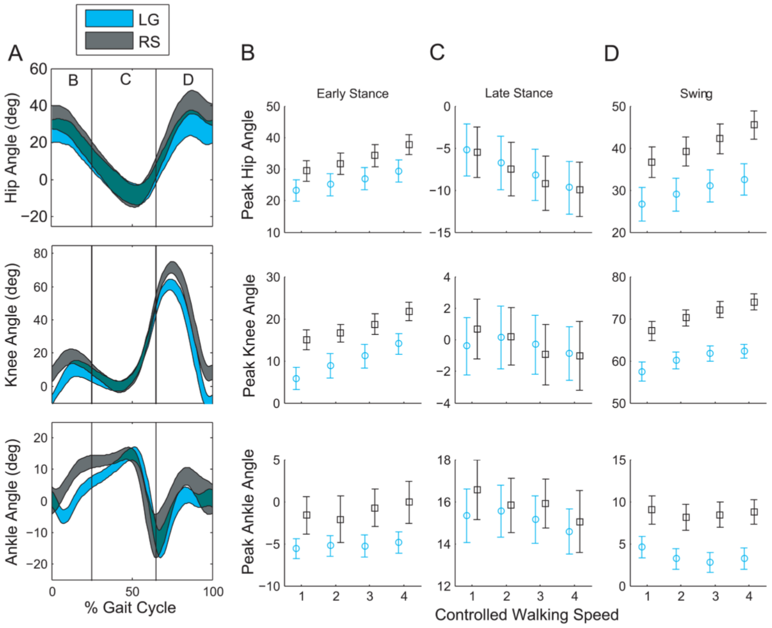

Figure 3.

Kinematics. A) Bands represent the mean ± standard deviation of the average joint angle across subjects. B–D) Average peak kinematic parameters are shown for each of the four controlled walking speeds (Fr = 0.06, 0.1, 0.16, and 0.23) on both surfaces. Error bars represent the 95% confidence intervals about the mean. Peaks during early stance (B) were identified between 0 and 25% of the gait cycle. Peaks during late stance (C) were found between 25 and 65% of the gait cycle. Swing phase peaks (D) were the maximum joint angle between 65 and 100% of the gait cycle. There were statistically significant main effects for walking speed ($p \leq 0.001$) for all peaks presented. There were also significant main effects for walking surface ($p < 0.014$) for all peaks except peak knee extension in late stance. Additionally, there were significant Speed × Surface interactions for all peaks expect peak knee flexion in early stance and peak ankle dorsiflexion in late stance.

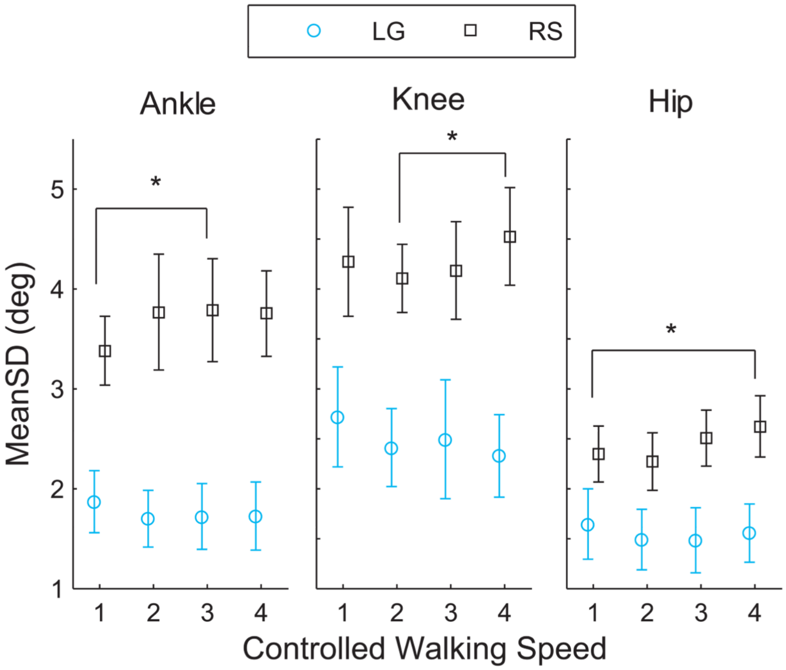

Figure 4.

Kinematic Variability. MeanSD is shown for the sagittal plane ankle, knee, and hip angles over the RS and LG at the four controlled speeds. Error bars represent ± 95 % confidence intervals about the mean. There was a significant main effect for walking surface ($p < 0.001$) and significant speed × surface interaction effects ($p < 0.05$) for all comparisons. Differences in speed on the RS determined from pos-hoc analysis are indicated by ‘*’.

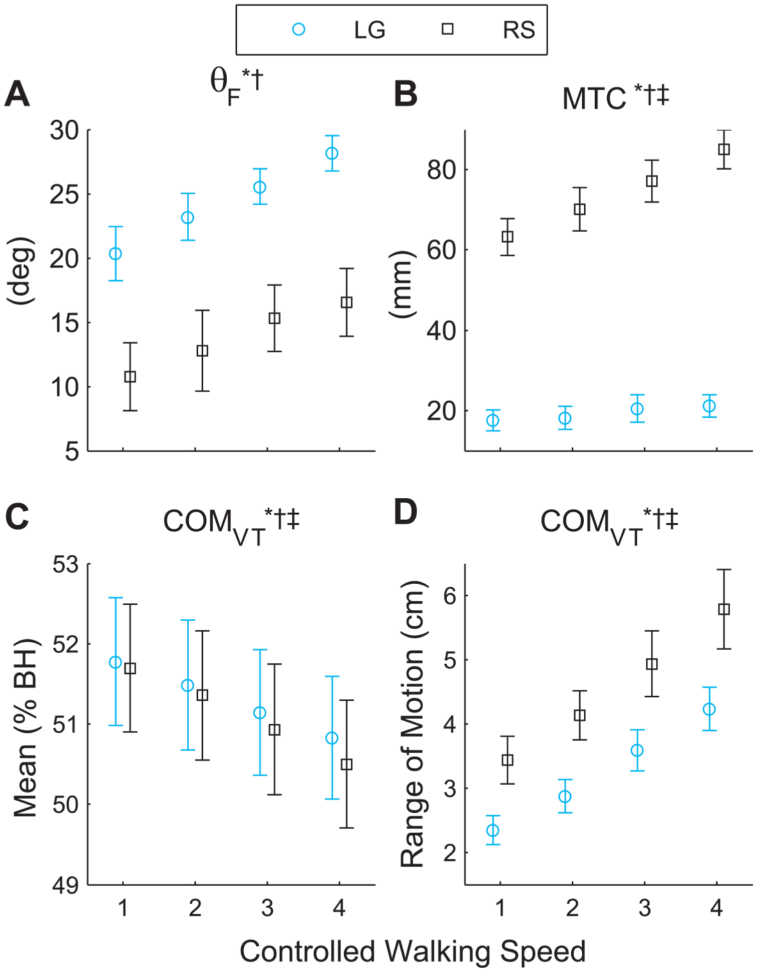

Figure 5.

A) The average foot angle, θ_F, at heel contact across subjects is shown for both the destabilizing loose rock surface (RS; '□') and level ground (LG; 'O') at each of the four controlled walking speeds (Fr = 0.06, 0.1, 0.16, and 0.23). B) The minimum toe clearance, MTC, is shown. C) The average position and B) range of motion of COM_{VT} are shown. Error bars represent ± 95% confidence intervals about the mean.

* Statistically significant main effects for walking speed ($p < 0.001$)

† Statistically significant main effects for walking surface ($p < 0.001$)

‡ Statistically significant speed × surface interactions ($p < 0.01$)