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The Influence of the Windlass Mechanism on Foot Joint Coupling

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ABSTRACT

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INTRODUCTION: Coupling in the distal foot may be due, at least in part, to the foot's windlass mechanism. This mechanism has been demonstrated passively, but its role in dynamic movement is still unclear. A systematic manipulation of metatarsophalangeal (MTP) mechanics may help determine to what extent distal foot coupling during dynamic and active movement is due to the windlass mechanism versus active muscle contractions or springlike ligaments. Furthermore, exploring the windlass mechanism in feet with varying foot structure may aid our understanding of the relationship between foot structure and foot function. PURPOSE: The overall purpose of this study is to investigate the kinematic and kinetic coupling between the MTP and midtarsal joints through a systematic manipulation of the windlass mechanism (achieved through methodical changes to MTP motion). Additionally, we aimed to explore the relationship between foot structure and the efficacy of the windlass mechanism during passive, active, and dynamic movement. METHODS: First, arch height and flexibility were measured using the Arch Height Index Measurement System. Next, participants performed four order-randomized conditions where MTP extension was isolated: 1) Seated Passive MTP Extension, 2) Seated Active MTP Extension, 3) Standing Passive MTP Extension, and 4) Standing Active MTP Extension. Lastly, participants performed three heel raise conditions that manipulated the starting position of the MTP joint: 1) Neutral: normal heel raise, 2) ToeExt: heel raise with the toes placed on an inclined surface of 30 degrees to put the MTP joint into extension, and 3) ToeFlex: heel raise with the toes placed on a declined surface of 30 degrees to put the MTP joint into flexion. All conditions were performed to a metronome of 40 beats per minute to control angular velocity. A kinetic multisegment foot model was created in Visual 3D software and used to calculate ankle, midtarsal, and MTP joint angles, moments, powers, and work. RESULTS: Kinematic coupling was approximately six times greater in the heel raise conditions compared to the isolated MTP extension conditions and suggests that the windlass mechanism only plays a small role in dynamic tasks. This is likely due to the greater involvement of active muscle contractions during heel raises. As the starting position of the MTP joint became increasingly extended, the amount of negative work at the MTP joint increased concomitantly with increased positive work done at the midtarsal joint, while net distal-to-hindfoot work remained unchanged. Our combined results suggest that there is substantial coupling within the distal foot, but this coupling is likely attributed to more than simple passive energy transfer from the windlass mechanism. Future investigations into the intrinsic foot muscle activation and biarticular muscle effects are likely needed to determine the source of this coupling. Lastly, the relationship between foot structure and function is still unclear and our results suggest that arch height or arch flexibility alone may not be adequate predictors of dynamic foot function.

Keywords: windlass mechanism, multisegment foot, foot energetics, heel raise

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Introduction

The foot's complex structure has traditionally made it difficult to model, resulting in overly simplified perspectives regarding its role in locomotion energetics. Early theoretical models of the foot's role in gait, such as the midtarsal locking theory (1), the twisted footplate model (2), and the arch-spring mechanism (3), all highlight the idea that the foot acts as a rigid lever for propulsion in late stance. Interestingly, this perspective is still frequently disseminated (e.g. (4-6)) despite many multisegment foot studies challenging this viewpoint (7-12). Instead, these studies have shown that substantial medial longitudinal arch (MLA) rise occurs (9-13) and the midtarsal joint generates considerable power during push-off (7, 14-16). As power is generated at the midtarsal joint, power is simultaneously absorbed at the 1st metatarsophalangeal (MTP) joint (7, 14-16), suggesting both kinematic and kinetic coupling between these two joints (15-17).

The coupling between the midtarsal and MTP joints may be due, at least in part, to the foot's windlass mechanism. A windlass is a crank and pulley system used to lift large loads over a drum. When this mechanism is applied at the human foot, the plantar aponeurosis functions as the cable, the toes as the crank, and the MTP joint as the drum (18). This mechanism has been demonstrated passively, where toe extension induces tension in the plantar aponeurosis which draws the calcaneus and head of the first metatarsal together, effectively causing the midtarsal joint to plantarflex (i.e., the MLA rises). Dynamically, when the MTP joint extends during late stance, this induced tension could facilitate positive power generation at the midtarsal joint during push-off (15-17); however, a systematic manipulation of MTP mechanics is needed to determine to what extent this distal foot coupling is due to the windlass mechanism (versus active muscle contractions or springlike ligaments).

If the windlass mechanism does influence the kinetic coupling between the MTP and midtarsal joints, this knowledge could enhance our understanding of human gait energetics, influence clinical treatment of gait deficiencies, and inform the design of assistive foot devices. The plantar flexor muscles at the ankle have historically been attributed as the primary generators of the power used for propulsion (19-22). But, multisegment foot studies have shown that this ankle power has been overestimated and between 27% (23) and 66% (24) of it should be attributed to the midfoot instead. Many foot muscles, both intrinsic and extrinsic, cross the midtarsal joint and thus contribute to the power generated at the joint (25, 26). If at least some of the positive power generated at the midfoot is transferred power from the windlass mechanism, then patient populations with decreased propulsion (either at the ankle or the midfoot), for example, could benefit from footplates and foot orthoses that simulate the energetic transfer of energy absorbed at the distal foot.

Foot structure may be correlated with how well the windlass mechanism functions (27), and therefore also possibly correlated with foot energetics. For instance, Lucas et al. found that individuals with an impaired windlass mechanism (i.e., delayed or absent midtarsal rise with MTP extension) have been shown to also have greater arch mobility, lower arches, and a pronated static foot compared to individuals with an intact windlass mechanism (27). However, in this study (27), motion at the midtarsal joint was not measured with motion capture technology and was only assessed based on if the investigator observed the arch rising. Furthermore, MTP extension was passively achieved by an investigator pushing on the participants' toes while they were in a standing position, and the efficacy of the windlass mechanism during active tasks was not investigated. Another research group showed that arch height may influence the windlass mechanism during walking (28), however the relationship between the efficacy of the windlass mechanism and other structural measurements, such as arch flexibility during dynamic tasks, is still unknown. Thus, an objective measurement of how arch flexibility influences the efficacy of the windlass mechanism during dynamic tasks is warranted.

Walking is one task where the windlass mechanism is engaged. Heel raises, though, are another task where the windlass mechanism is dynamically engaged and could provide a more controlled environment to systematically manipulate the MTP joint, and thus the windlass mechanism. Furthermore, motion at the midfoot and ankle as well as ankle power during heel raises and push-off during walking are significantly correlated (29), suggesting that heel raises may serve as an adequate substitute for examining how the windlass mechanism may function during walking.

The overall purpose of this study was to investigate the kinematic and kinetic coupling between the MTP and midtarsal joints through a systematic manipulation of the windlass mechanism (achieved through methodical changes to MTP motion). To satisfy this overall purpose, there were several specific aims. First, we wanted to explore the relationship between task complexity and the amount of kinematic coupling within the distal foot, hypothesizing that coupling would decrease with task complexity. Secondly, we wanted to investigate how changes in MTP motion affect the mechanical work done at the midtarsal and MTP joints. We hypothesized that as MTP motion is systematically manipulated during dynamic movement (i.e., heel raises) changes in MTP joint negative work will be proportional to opposing changes in midtarsal positive work, while distal-to-hindfoot work (which covers the net contributions of all foot joints distal to the hindfoot) (30) will remain constant across all conditions. The final aim was to explore the relationship between foot structure measures and the efficacy of the windlass mechanism during passive and dynamic movement. We hypothesized that low arch height and high arch flexibility will be correlated with a less active windlass mechanism (i.e., less midtarsal motion per degree of MTP extension, smaller midtarsal peak power, and less positive midtarsal work).

Methods

Participants

Twenty-eight participants (11 female, 17 male; age: 24.3 ± 4.6; height: 1.75 ± 0.07 m; body mass: 74.6 ± 12.8 kg) visited the Biomechanics Lab on the university's campus for a two-hour visit. Participants were excluded if they had a history of musculoskeletal or neurological disease, had undergone any surgery in the lower extremities, or had a serious lower extremity injury that resulted in an inability to resume all previous physical activities. Before any data collection, participants were asked to thoroughly read and sign an IRB-approved informed consent form.

Procedures

First, investigators used the Arch Height Index Measurement System (JAK Tool & Model, NJ, USA) to determine the height and flexibility of the participant's arch. Only the left foot was measured, as there is no difference between left and right sides for arch height index measurements (31, 32), and lab set-up made the left foot the preferred side on which to perform all further testing. Arch flexibility was calculated using the following equation, where 'AH' is the height of the foot's dorsum from the floor at half of the total foot length, and 'BW' is body weight (32):

$$Arch\ Flexibility\ \left(\frac{cm}{kg}\right) = \frac{AH_{sitting} - AH_{standing}}{0.4 * BW} * 100 \qquad (1)$$

In order to get arch flexibility into the same units reported by Zifchock et al. (mm/kN) (32), the value calculated from this equation was multiplied by 10,000 and divided by 9.8. A low arch flexibility value indicates a stiff arch, and a high arch flexibility value indicates a flexible arch (32). For this study, we targeted participants with varying foot structures so that we had a range of arch heights and flexibilities. Participant's height and weight were also measured.

After all preliminary data was obtained, the left foot was outfitted with a multisegment foot model, while the right foot was modeled as a single segment. The marker set used for this study closely resembled the multisegment foot model developed by Bruening et al. (8) but with a few modifications (see Table 1 for marker set details).

Following marker placement, participants performed four order-randomized tasks where isolated MTP extension was achieved either passively or actively: 1) Seated Passive MTP Extension, 2) Seated Active MTP Extension, 3) Standing Passive MTP Extension, and 4) Standing Active MTP Extension. During the passive trials, an investigator passively extended the participant's MTP joint to its end range of motion 10 consecutive times for two sets to a metronome of 40 beats per minute (bpm). Standing Passive MTP Extension was achieved by having the participants stand on a block two feet off the ground and placing their feet so that their toes were off the edge. This set-up allowed the investigator to push the MTP joint into extension without blocking the view of the motion capture cameras. During the active trials, participants were instructed to extend their 1st MTP joint as far as possible to the metronome. Set up during Standing Active MTP Extension was identical to Standing Passive MTP Extension. These isolated tasks allowed us to investigate with motion capture the kinematic coupling that occurs between MTP and midtarsal joints when the windlass mechanism is passively and actively engaged.

Next, participants performed three double-leg heel raise conditions that manipulated the starting position of the MTP joint during dynamic movement. These three dynamic MTP extension conditions were: 1) Neutral: normal heel raises (control), 2) ToeExt: heel raises with the toes placed on an inclined surface of 30 degrees to put the MTP joint into extension, and 3) ToeFlex: heel raises with the toes placed on a declined surface of 30 degrees to put the MTP joint into flexion. To achieve the inclined and declined surfaces, blocks were placed on two adjacent in-ground force plates (Figure 1). The toes were placed on the angled surface mounted to one force plate, while the rest of the foot was placed on a flat surface on the other plate. The foot segments were placed on different force plates to partition the ground reaction forces (GRF) under each segment (14). Force plates were zeroed after the blocks were mounted and between each condition. All heel raise conditions had two sets of 10 consecutive trials and were performed to a metronome of 40 bpm to control ankle angular velocity. A tripod was placed in front of participants during heel raises, which they could lightly touch with their fingertips to help them maintain balance during the different conditions. To help with achieving the same height across all three conditions, participants wore a headband with a marker secured to the top and tried to match the height of this marker with a target marker visible from an orthogonal front view on a screen in front of them. The position of this target marker did not change between conditions. These controlled heel raises allowed us to evaluate associated changes in foot kinematics and energetics during a dynamic task where the windlass mechanism is actively and dynamically engaged.

Data Analysis

Kinematic data was collected at 200 Hz and low-pass filtered (Butterworth) at 6 Hz, while kinetic data was captured at 1000 Hz and low-pass filtered at 50 Hz. Motion capture trajectories were exported from Qualisys Track Manager software (Qualisys, Goteborg, Sweden) and imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA). A kinetic multisegment foot model was created using Visual 3D (8). After all data was imported into Visual 3D, ankle, midtarsal, and MTP joint angles, moments and powers (including distal-to-hindfoot power (30)) were calculated. Angles were calculated using a typical Euler/Cardan rotation sequence (1-flex/ext, 2-ab/ad, 3-int/ext rotation). Work was calculated as the integration of the power curve during the upward phase of the heel raise. To account for small changes in the height achieved across the heel raise conditions, work was calculated from the start of the heel raise to the lowest height achieved during any of the three heel raise conditions. All kinetic variables were scaled by body weight.

To measure the amount of kinematic coupling that occurs between the MTP and midtarsal joints, the slope of the line created by plotting the angle curve (during the upward phase of the heel raise) for the midtarsal joint versus the MTP joint was calculated. This slope (known from now on as 'distal foot coupling ratio' or DFCR); (ΔMidtarsal Angle) / (ΔMTP Angle) was then used as a metric to explain the amount of kinematic coupling between these two joints during both the dynamic MTP extension conditions and the isolated MTP extension conditions.

Statistical Analysis

To determine if the amount of kinematic coupling changed across all conditions, a repeated measures ANOVA was done to compare the DFCR metric from each condition. A series of repeated measures ANOVAs were done for MTP negative work, midtarsal positive work, and ankle positive work across the three heel raise conditions. To verify that changes in MTP and midtarsal joint work changed proportionally, another repeated measures ANOVA was used to assess differences in distal-to-hindfoot work (30). For each ANOVA, Mauchly's test for sphericity was tested and corrected for if necessary. A Holm post hoc test was applied if the main effect showed significance ($\alpha = 0.05$).

A series of correlations were conducted for each condition to assess the relationship between arch flexibility and standing arch height and DFCR. Another correlation, for the heel raise conditions only, was conducted to assess the relationship between arch flexibility, standing arch height and midtarsal peak power and midtarsal positive work.

Results

Kinematic Coupling: Distal Foot Coupling Ratio Across All Conditions

Contrary to our hypothesis, DFCR increased with task complexity, with all the dynamic MTP extension conditions (Neutral: 0.765 ± 0.15, ToeExt: 0.838 ± 0.233, ToeFlex: 0.794 ± 0.126) having a larger kinematic coupling ratio than the isolated MTP extension conditions ($p < 0.001$; Figure 2). There was no statistical difference in DFCR between heel raise conditions. However, when looking only at the relationship between isolated MTP extension conditions, both standing conditions (Standing Passive: 0.087 ± 0.03, Standing Active: 0.077 ± 0.04) had less coupling compared to both seated conditions (Seated Passive: 0.130 ± 0.03, Seated Active: 0.122 ± 0.04; Figure 2).

Kinetic Coupling: Joint Work During Heel Raises

As the starting position of the MTP joint became increasingly extended, the amount of negative work done at the MTP joint increased (ToeExt: −0.029 ± 0.01, Neutral: −0.021 ± 0.009, ToeFlex: −0.01 ± 0.008; $p < 0.001$; Figure 3). Similarly, midtarsal positive work was greatest for ToeExt and smallest for ToeFlex (ToeExt: 0.151 ± 0.035, Neutral: 0.142 ± 0.038, ToeFlex: 0.124 ± 0.035); $p < 0.01$; Figure 3).

In support of our hypothesis, distal-to-hindfoot work was not significantly different between Neutral, ToeExt, and ToeFlex (Figure 3). This verified that changes in MTP negative work and midtarsal positive work changed proportionally across conditions. Additionally, ankle positive work was not significantly different across all three conditions, indicating that the ankle did not compensate for changes at the MTP joint.

Correlation: Arch Flexibility and Arch Height Versus Distal Foot Coupling Ratio

The average standing arch height index was 0.33 ± 0.02, ranging from 0.29 to 0.38. The average arch flexibility was 13.99 ± 5.9 mm/kN, ranging from 3.52 to 27.19 mm/kN.

Of the isolated MTP extension conditions, arch flexibility was moderately and negatively correlated with DFCR during Seated Active MTP Extension ($r = -0.42$, $p = 0.03$), and standing arch height index was weakly and positively correlated with DFCR during Standing Active MTP Extension ($r = 0.39$, $p = 0.04$). However, all other isolated conditions were not significantly correlated with arch flexibility or standing arch height.

Of the dynamic conditions, arch flexibility was moderately and positively correlated with DFCR during Neutral ($r = 0.402$, $p = 0.03$) and only weakly correlated with DFCR during ToeFlex ($r = 0.369$, $p = 0.05$). But arch flexibility was not correlated with DFCR during ToeExt, or with midtarsal peak power and midtarsal positive work. Arch height was not significantly correlated with any variable during heel raises.

Discussion

The overall purpose of this study was to investigate coupling within the distal foot during tasks of varying complexity with the goal of garnering greater understanding of the windlass mechanism's role during dynamic movement. Contrary to our hypothesis, as task complexity increased from isolated MTP extension to dynamic MTP extension, kinematic coupling increased indicating more midtarsal plantarflexion with each degree of MTP extension. Regarding kinetic coupling, our hypothesis that changes in MTP joint negative work would be proportional to midtarsal positive work was met. And lastly, our results exploring the relationship between foot structure and foot coupling were inconclusive.

Kinematic Coupling and Task Complexity

Any midtarsal motion captured during Seated Passive MTP Extension is likely due to the MTP extension (i.e., the windlass mechanism), as subjects were relaxed during this condition. However, muscle activity was not measured and thus the possibility of active muscle contractions cannot be completely ruled out; although care was taken to ensure investigators felt no active assistance or resistance when pushing the MTP joint into extension. If motion at the midtarsal joint was entirely due to the windlass mechanism during Seated Passive MTP Extension, then the coupling ratio for this condition could be used as a baseline to assess the contribution of the windlass mechanism to the coupling ratio during other tasks. For example, the DFCR for Neutral heel raise was 6 times that of the seated passive condition, thus roughly 5/6 of that motion is likely not due to the windlass mechanism. Contrary to our hypothesis, the dynamic conditions all had larger DFCRs compared to the isolated MTP extension conditions, which indicates greater midtarsal plantarflexion for each degree of MTP extension. Other recent work has also found that arch rise was significantly greater during dynamic movement (i.e., walking) compared to passive MTP extension during sitting and standing (33). During dynamic movement like heel raises, there will be more muscular involvement to raise the center of mass compared to a less complex task where MTP joint extension was isolated while standing or sitting. Thus, during dynamic tasks the windlass mechanism may only play a minor role in arch rise compared to the role of active muscle contractions.

Interestingly, the standing DFCR for both passive and active conditions were slightly smaller than both the seated DFCRs. The reason for this slight drop in DFCR is not completely clear. It may be due to the static loading experienced by the MLA during standing, which flattens the arch (31), slightly changing the foot's posture and the tension in the plantar aponeurosis. Additional research may be needed to better understand how position influences coupling.

MTP Versus Midtarsal Work During Dynamic Movement

In support of our hypothesis, work generated at the midtarsal joint changed proportionally to the work absorbed at the MTP joint during heel raises, as indicated by the consistency of distal to hindfoot work across conditions. Interestingly, when examining how each joint changed independently, ToeExt had the greatest power generation and absorption and ToeFlex had the least (Figure 4C). Since power is the product of joint moment and angular velocity, some insights into these findings are possible from angle and moment graphs. For angles, although there was greater midtarsal plantarflexion in ToeExt at the start of heel raises, this did not result in a greater peak angle or angular velocity compared to Neutral (Figure 4A). Instead, the midtarsal plantarflexion moment increased throughout the movement for ToeExt (Figure 4B). This could be due to a more advantageous muscle force-length positioning in the ToeExt starting position. In contrast, the ToeFlex condition exhibited less peak midtarsal plantarflexion and slightly lower moment compared to Neutral, perhaps due to being placed in a disadvantageous position. Future work employing fine-wire EMG of intrinsic foot musculature and musculoskeletal modeling of the numerous biarticular muscles crossing these joints may be needed to clarify these differences.

Other work supports the notion that changes in work done at the MTP and midtarsal joints occur concomitantly. When comparing the power profiles of runners with varying foot strikes, Bruening et al. found that forefoot strikers had greater MTP negative work concurrent with greater midtarsal positive work (13). Furthermore, the concomitant changes in MTP and midtarsal work is evident when walking speed is manipulated; as speed increased, MTP negative work and midtarsal positive work both increased (34). Considering the results of the current study in conjunction with previous work, there is likely kinetic coupling within the joints of the foot.

Arch Flexibility and Arch Height Versus Kinematic Coupling

We based our hypothesis that high arch flexibility and low arches would be related to a less efficient windlass mechanism (i.e., smaller DFCR) on the results from a study done by Lucas and colleagues (27). In partial support of our hypothesis, flexible arches had a smaller DFCR during Seated Active MTP extension, and low arches had a smaller DFCR during Standing Active MTP extension. Contrary to our hypothesis, though, stiff arches had a smaller DFCR during both Neutral and ToeFlex heel raises. Thus, our results are inconclusive, and we cannot determine if individuals with flexible or low arches have a less efficient windlass mechanism.

A traditional clinical assumption is that high arches are stiff and low arches are flexible (35, 36). However, recent work demonstrates that many arch flexibility types exist within arch height types (32), and that during running there is no correlation between arch height classifications and arch flexibility (37). The current study supports the notion that there is a varied distribution of arch flexibilities within the arch height categories, as we found that 21% of our participants had both stiff and low arches while 10% had both flexible and high arches. To classify the arches of our participants, we used the classifications of Zifchock et al. (32) for arch flexibility, grouping the 'very-stiff' and 'stiff' categories into one category called 'stiff' (similar grouping was done for the ‘very-flexible’ and ‘flexible’ categories). For arch height, the average of the cut-offs specified by Hillstrom et al. (38) and Williams et al. (39) was used. Perhaps if we recruited individuals that had both stiff and high arches or flexible and low arches, a stronger correlation between foot structure and windlass mechanism efficiency would have been observed. Future studies could explore these specific populations as it may provide useful insight for clinical applications.

While our results are inconclusive regarding the relationship between the windlass mechanism and foot structure, they provide evidence that foot structure does not have a strong correlation with foot function. The research exploring the relationship between static structure and dynamic foot function is mixed. For example, Magalhães et al. found that individuals with greater foot mobility had increased range of motion at the midfoot joint complex during walking compared to individuals with less foot mobility (40). Contrarily, Hunt et al. found no correlation between foot structure and midfoot range of motion during stance (41). Thus, the relationship between foot structure and function is still unclear and our results suggest that arch height or arch flexibility alone may not be adequate predictors of dynamic foot function.

Conclusions

When MTP motion is systematically manipulated during heel raises, the changes in midtarsal positive work and MTP negative work changed proportionally. This indicates that there is likely kinetic coupling between these two joints. Furthermore, the amount of kinematic coupling within the distal foot increased substantially during heel raises compared to when the MTP joint was passively extended in a non-weight-bearing position. Thus, if the windlass mechanism influences power generation at the midtarsal joint, it is likely a small role secondary to active muscle contractions or other mechanisms. However, further study into the windlass mechanism's role in foot energetics is still needed. Additional research is also needed into what other mechanisms are contributing to the coupling within the foot. Particularly, there is a need for further research involving measures of muscle contractions within the foot during dynamic tasks. Lastly, the relationship between foot structure and function is still unclear and our results suggest that arch height or arch flexibility alone may not be adequate predictors of dynamic foot function.

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Table 1. Marker Names and Description of Placement.

Marker Name	Description of Placement
HEAD	Top of the head
ASIS	Anterior superior iliac spine
PSIS	Posterior superior iliac spine
TH1-4*	Thigh cluster 1-4; rigid cluster on lateral thigh
LKN	Lateral epicondyle of femur
MKN	Medial epicondyle of femur
SHK1-4*	Shank cluster 1-4; rigid cluster on lateral shank
LANK	Lateral malleolus
MANK	Medial malleolus
PCL*#	Proximal calcaneus
DCL*	Distal calcaneus; apex of calcaneal tuberosity
LCL*#	Lateral calcaneus
MCL*#	Medial calcaneus
CUB#	Cuboid; lateral cuboid
NAV#	Navicular; navicular tuberosity
MB1#	Dorsal surface of the base of the 1st metatarsal
MB4	Dorsal surface of the base of the 4th metatarsal
MHD#	Dorsal surface1st metatarsal head; dorsum of head of the 1st metatarsal
MH1	1st Metatarsal head; medial aspect of head of the 1st metatarsal
23MH#	2nd and 3rd Metatarsal heads; midpoint of heads of the 2nd and 3rd metatarsals
MH5	5th Metatarsal head; lateral aspect of head of the 5th metatarsal
HAL#	Hallux; dorsum of the distal phalanx of the hallux

*Tracking Marker
#Left side only

Figure 1. Heel Raise Conditions
A. Neutral heel raise. B. ToeExt heel raise. C. ToeFlex heel raise.

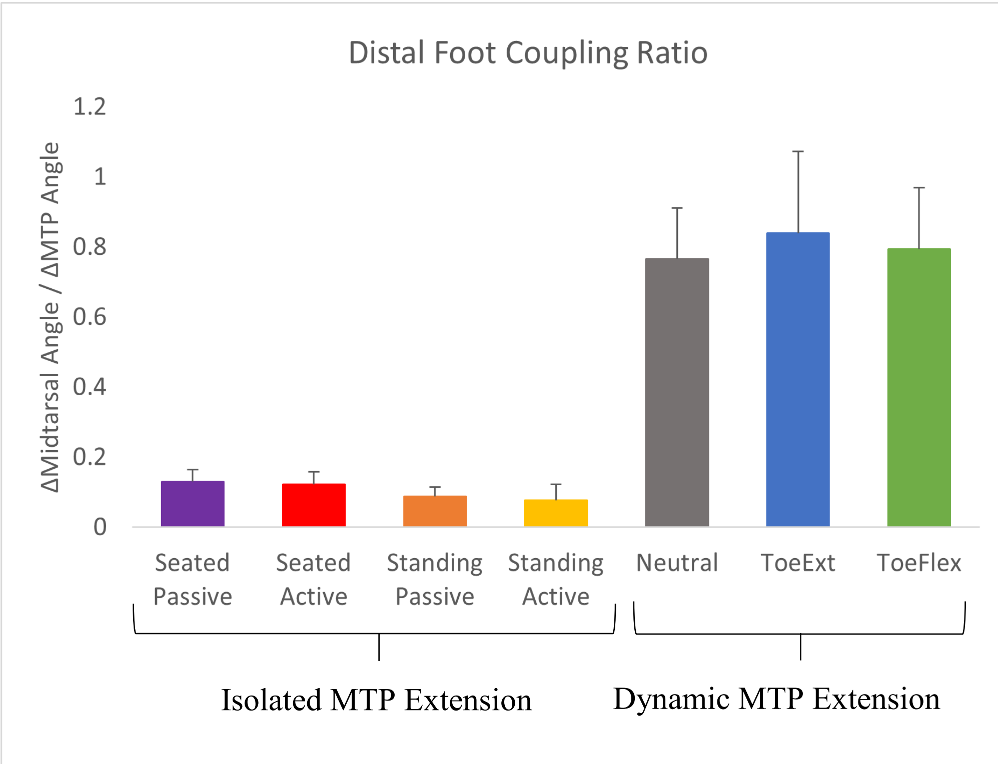

Figure 2. Distal Foot Coupling Ratio for All Conditions
Distal foot coupling ratio (ΔMidtarsal Angle / ΔMTP Angle). Bars represent means with standard deviation error bars across all conditions. Dynamic MTP Extension conditions had greater coupling ratios than all the Isolated MTP Extension conditions ($p < 0.001$). Within the Isolated MTP Extension conditions, both seated conditions had significantly greater DFCR than both standing conditions ($p < 0.05$).

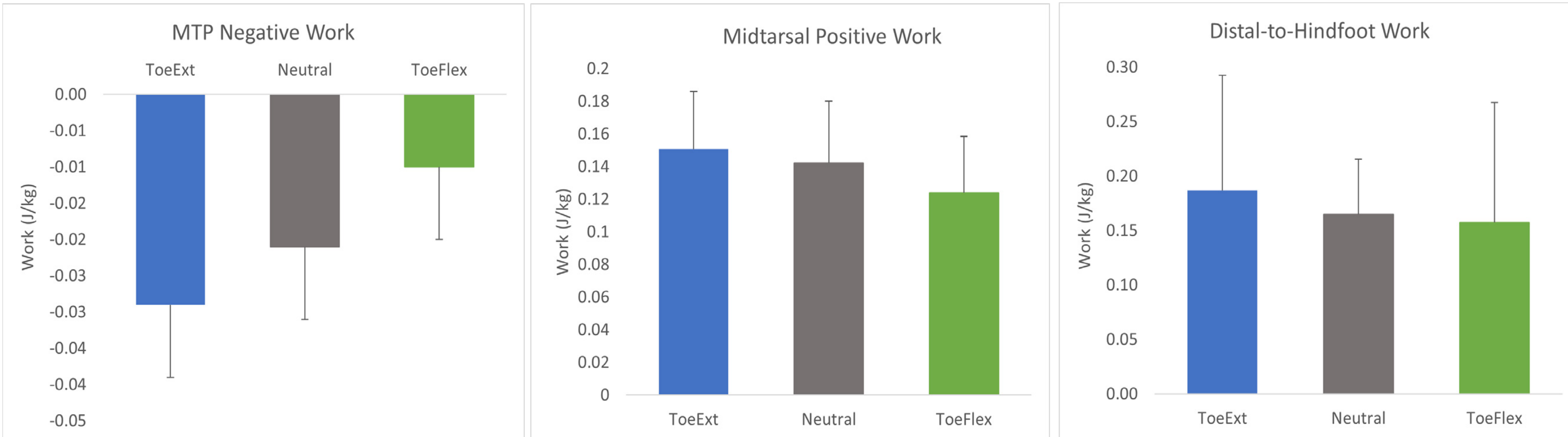

Figure 3. MTP, Midtarsal, and Distal-to-Hindfoot Work During Heel Raise Conditions
ToeExt, Neutral, and ToeFlex heel raise conditions. Bars represent means with standard deviation error bars. All conditions were significantly different ($p < 0.01$) for MTP and Midtarsal, while there was no significant difference between conditions for Distal-to-Hindfoot work.

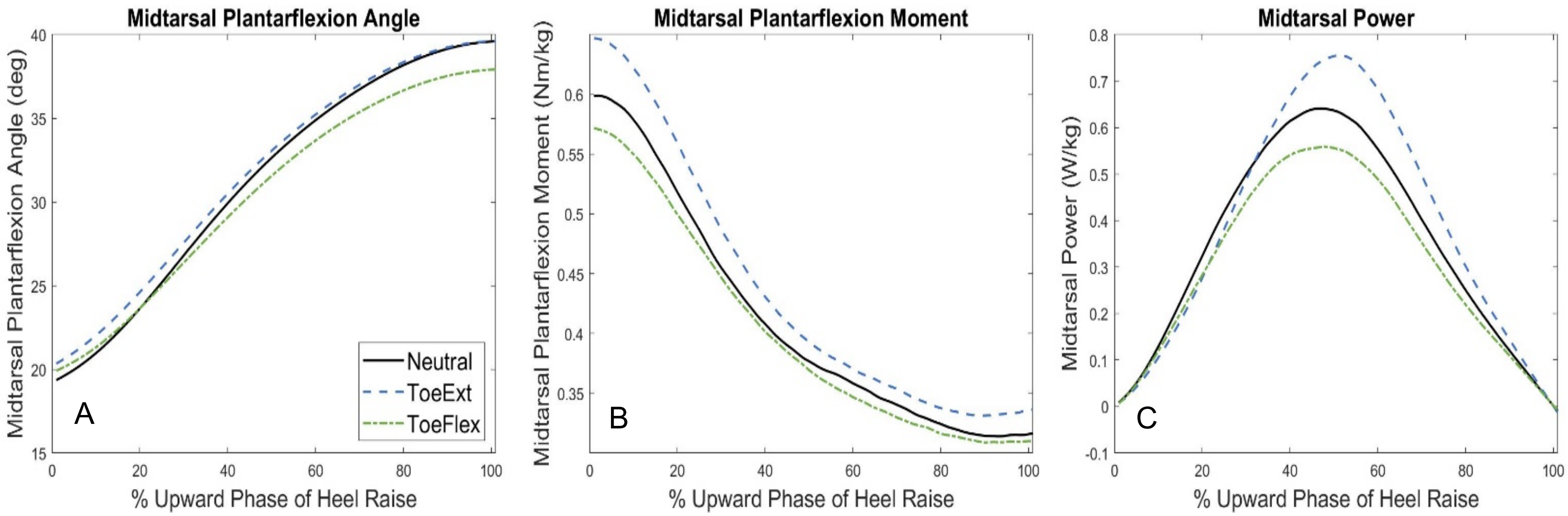

Figure 4. Midtarsal Angle, Moment, and Power During Heel Raise Conditions
Mean Midtarsal angle, moment, and power during the upward phase of Neutral (black, solid line), ToeExt (blue, dashed line), and ToeFlex (green, dash-dot line).A. Midtarsal plantar flexion angle; B. Midtarsal plantarflexion moment; C. Midtarsal power