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# Unholey shoes: Experimental considerations when estimating ankle joint complex power during walking and running

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## ABSTRACT

For studies that aim to assess biological ankle function, calculating ankle joint complex (AJC) power between the calcaneus and shank is recommended over conventional inverse dynamics estimates between a rigid-body foot and shank. However, when designing a new experiment, it remains unclear whether holes should be cut in footwear to permit motion tracking via skin-mounted markers, or whether marker placement locations should be tightly controlled across conditions. Here we provide data to assist researchers in answering these questions. We performed a gait analysis study of walking (0.8, 1.2, 1.6 m·s<sup>-1</sup>) and running (2.6, 2.8, 3.0 m·s<sup>-1</sup>) while subjects ( $N = 10$ ) wore custom-modified footwear, which allowed markers to be placed either on the shoe, or on the skin via cut-out windows in the shoes. First, we compared foot markers affixed to the skin vs. on the same locations on the shoe. Using statistical non-parametric mapping techniques, we discovered that skin vs. shoe markers had no statistically significant effect on net AJC power estimates throughout stance phase, for all walking and running speeds. Second, we compared calcaneal markers in the nominal shoe configuration vs. markers in a nearby location (~27 mm below) on the shoe. We observed significant differences when marker placement on the shoe was varied, which may be relevant to repeated-measures study designs. The results suggest that when computing AJC power for walking and running, you may want to put down the scissors (i.e., forego cutting holes in your footwear), and instead pick up a Sharpie® (pen) or use a template, to maintain consistent marker placement across trials and conditions.

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## 1. Introduction

Inverse dynamics analysis is typically used to compute net ankle joint power, with conventional models treating the foot as a single rigid-body. However, this rigid foot assumption has been found to overestimate biological ankle power contributions during walking (Bruening et al., 2012; Dixon et al., 2012; Zelik and Honert, 2018). In response to these observations, we recently recommended the use of Ankle Joint Complex (AJC) power, computed between the shank and calcaneus (heel), to better estimate biological ankle function (Zelik and Honert, 2018). Introducing this alternative power calculation engenders several practical questions. In particular, it is not clear (i) whether the calcaneus should be tracked using skin-mounted markers (i.e., visible via windows

cut in footwear material), or (ii) how sensitive the AJC power estimation is to variation in calcaneal marker placement locations.

Several studies, mostly focused on running, provide insight into kinematic differences resulting from variations in how/where motion tracking markers are affixed. When comparing shoe-mounted markers to the gold-standard method of bone-pin tracking, Reinschmidt et al. (1997b, 1997a) observed kinematic differences of varying magnitudes in all three planes of motion. Furthermore, the prevailing belief is that a skin-mounted marker set is superior to a shoe-mounted marker set when calculating ankle and foot kinematics during running and side-stepping (Alcantara et al., 2018; Arnold and Bishop, 2012; Reinschmidt et al., 1992; Trudeau et al., 2017; van Gheluwe et al., 1995). However, when comparing kinematics from skin vs. shoe-mounted markers, the period in the gait cycle when differences occur has not been consistently agreed upon. For example, one study reported initial contact (Alcantara et al., 2018) and another reported later in stance (van Gheluwe et al., 1995). Given the vastly different interests of the biomechanics community, it is beneficial

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to understand where, within stance phase, disparate results may occur. For instance, some studies may be interested in weight-acceptance dynamics (early stance), others might explore tendon energy storage in mid-stance, and others may investigate push-off dynamics near the end of stance phase.

Presently, it remains unclear whether the choice of foot marker location influences AJC power estimates during locomotion. This open question remains because of the limited data on non-running tasks (e.g., walking), and also because the effect on AJC power cannot be inferred from kinematic measures alone - net joint moments must also be considered.

When designing an experiment that involves estimating ankle joint kinetics, it would be beneficial to know if holes should be cut in footwear to permit tracking of underlying foot motion via markers mounted on the skin, and whether precise marker placement locations should be tightly controlled across footwear conditions (given practical challenges associated with maintaining consistency across subjects, test sessions and conditions). The purpose of this study was to address these questions by quantifying differences in AJC power during walking and running when foot markers were placed i) on the shoe vs. skin, and ii) in different locations on the shoe.

## 2. Methods

### 2.1. Overview

We performed an instrumented gait analysis study computing AJC power at various walking and running speeds. All conditions were performed shod with custom-modified footwear that allowed markers to be placed either on the exterior of the shoe, or on the skin via cut-out windows in the shoes. First, we compared foot markers affixed to the skin (SKIN) vs. markers placed on the same locations on the shoe (SHOE; Fig. 1). For this, we recorded data in two separate trials per gait speed to ensure markers were placed in a near-identical location for both conditions. Second, we compared calcaneal markers in the nominal SHOE configuration vs. markers in a nearby location (SHOE<sub>alt</sub> configuration), both of which were captured in the same trial for a given gait speed. The study design is depicted in Fig. 1.

### 2.2. Participants

Healthy adults ( $N = 10$ : 3 male, 7 female; age:  $23.8 \pm 2.9$  years; mass:  $66.1 \pm 8.9$  kg; height:  $1.7 \pm 0.1$  m; mean  $\pm$  s.d.) provided



**Fig. 1.** Depiction of study design. Question one (upper): skin-mounted motion capture markers (SKIN) vs. shoe-mounted markers (SHOE) for ankle joint complex power estimates in both walking and running. Data were collected in separate trials. Question two (lower): SHOE vs. shoe-mounted markers placed in a nearby location (SHOE<sub>alt</sub>) with the same forefoot markers used in both configurations. Data for SHOE and SHOE<sub>alt</sub> were collected in the same trial per gait speed.

informed written consent to participate in the current study, which was approved by the Institutional Review Board of Vanderbilt University. Participants were required to be free from diseases, disorders or conditions that could affect their ability to perform physical activity (e.g., cardiorespiratory issues, musculoskeletal injury). We provided footwear for the study (men's size 6.5 and 9.5 U.S., Champion Gusto Cross Trainer, Winston-Salem, NC, USA) and participants were excluded if this footwear did not fit.

### 2.3. Experimental design

Data collection commenced with the application of a retro-reflective marker set to the right lower limb of the participants. Similar to the placements outlined in Zelik and Honert (2018), the target anatomical locations were the thigh (four), femoral condyles of the knee (two), shank (four), malleoli (two), calcaneus (three; posterior, medial and lateral aspects), lower-calcaneus (three;  $26.9 \pm 3.3$  mm below calcaneal markers for the SHOE<sub>alt</sub> condition only) and forefoot (two; distal heads of the first and fifth metatarsals). A helical knee joint axis and ankle joint center were computed from functional calibration trials and defined relative to each proximal segment (Schwartz and Rozumalski, 2005).

Participants walked at three speeds (0.8, 1.2 and  $1.6 \text{ m}\cdot\text{s}^{-1}$ ) and ran at three speeds ( $2.6$ ,  $2.8$  and  $3.0 \text{ m}\cdot\text{s}^{-1}$ ), first with foot markers (14 mm in diameter) on the skin (SKIN configuration; six trials) and then again with markers on the shoe, in SHOE and SHOE<sub>alt</sub> configurations (six trials). When the participant was deemed, by observation, to have reached a consistent gait pattern for a given trial, 30 s of three-dimensional marker trajectory data were collected using a ten-camera Vicon MX system (200 Hz; Oxford Metrics, Oxford, UK) calibrated to an accuracy of  $< 0.3$  mm. Synchronized ground reaction force (GRF) data from a split-belt instrumented treadmill (1000 Hz; Bertec Corporation, Columbus, OH, USA) were also collected simultaneously.

### 2.4. Marker and shoe modifications

Circular windows were cut into each shoe such that all five foot markers could be affixed directly to the underlying skin (SKIN configuration). Alternatively, these windows could be covered with fabric (via hook and loop attachments) so markers could be placed in the same location but directly affixed to the shoe (SHOE configuration). For the SKIN configuration, custom-made extended marker bases (height:  $\sim 20.0$  mm; Fig. 1) were used to ensure marker visibility, and to prevent contact between the marker and/or base and the shoe, such that the markers could move independently of the surrounding footwear material. The circular window diameter was restricted to 20 mm (area =  $314 \text{ mm}^2$ ), in order to maintain the structural integrity of the shoe (Arnold and Bishop, 2012; Shultz and Jenkyn, 2012). Standard marker bases (height:  $\sim 2.1$  mm) were used for the SHOE and SHOE<sub>alt</sub> configurations. The goal of the SHOE<sub>alt</sub> configuration was to isolate the effect of calcaneal tracking marker placement. As such, forefoot marker locations were held constant between the SHOE and SHOE<sub>alt</sub> conditions.

### 2.5. Data processing and analyses

Kinematic and GRF data were low-pass filtered using a zero-lag fourth-order Butterworth filter with cut-off frequencies of 8 Hz and 15 Hz, respectively. Stance phases (bound by right limb foot contact and toe-off events, as identified using GRF data) were extracted for further processing. Six degree-of-freedom AJC power was calculated by summing the translational and rotational powers due to the motion of the shank relative to the calcaneus (Eq. (1); Zelik and Honert, 2018).

$$AJC \text{ power} = \vec{M}_{ank} \cdot (\vec{\omega}_{shank} - \vec{\omega}_{calc}) + \vec{F}_{ank} \cdot (\vec{v}_{ank,shank} - \vec{v}_{ank,calc}) \quad (1)$$

where  $\vec{M}_{ank}$  is the three degree-of-freedom net ankle joint moment,  $\vec{\omega}_{shank}$  and  $\vec{\omega}_{calc}$  are the angular velocities of the shank and calcaneus segments, respectively,  $\vec{F}_{ank}$  is the net ankle force on the shank, and  $\vec{v}_{ank,shank}$  and  $\vec{v}_{ank,calc}$  are the translational velocities of the ankle based on shank and calcaneus motion, respectively.

All estimates were mass-normalized, and normalized to stance phase.

### 2.6. Statistical analyses

To address the objectives of this study we plotted AJC power for SKIN vs. SHOE, and for SHOE vs. SHOE<sub>alt</sub>. Power differences were evaluated using the statistical non-parametric mapping source code (spm1d version M.0.4.5 in Matlab; MathWorks, Inc., Natick, USA), which was employed to compare our continuous time-series power estimates at each percentage of stance phase. This method allowed us to assess if and when a change in marker configuration produced a statistically significant difference in AJC power curves. Similar to typical repeated-measures analyses on discrete data points, our analysis involved an initial check of normality, followed by statistical comparisons.

Analyses of variance (ANOVA) and t-tests were performed using the non-parametric inference tools built into spm1d (Pataky et al., 2015), which follow the permutation test procedures detailed in Nichols & Holmes (2002). As such, four repeated-measures two-way ANOVA tests with an alpha level of 0.05 were applied, accounting for speed and marker configuration factors:

- SKIN vs. SHOE for walking at 0.8, 1.2 and 1.6 m·s<sup>-1</sup>
- SKIN vs. SHOE for running at 2.6, 2.8 and 3.0 m·s<sup>-1</sup>
- SHOE vs. SHOE<sub>alt</sub> for walking at 0.8, 1.2 and 1.6 m·s<sup>-1</sup>
- SHOE vs. SHOE<sub>alt</sub> for running at 2.6, 2.8 and 3.0 m·s<sup>-1</sup>

Following this, we conducted post hoc t-tests with a Bonferroni correction to account for six speed comparisons (adjusted alpha level of 0.0083).

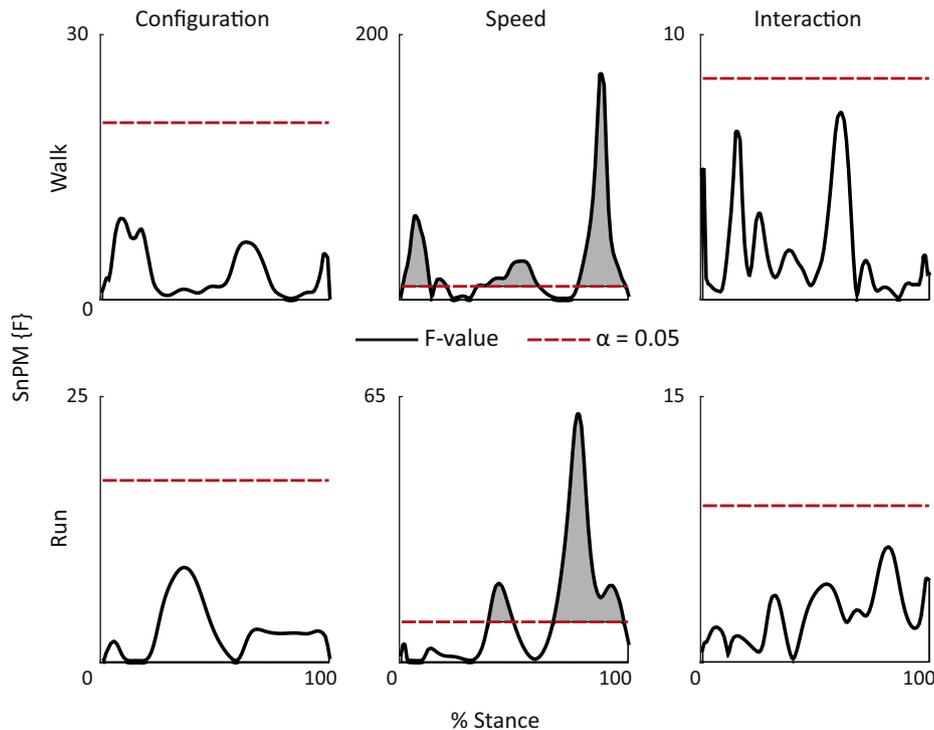
## 3. Results

### 3.1. SKIN vs. SHOE

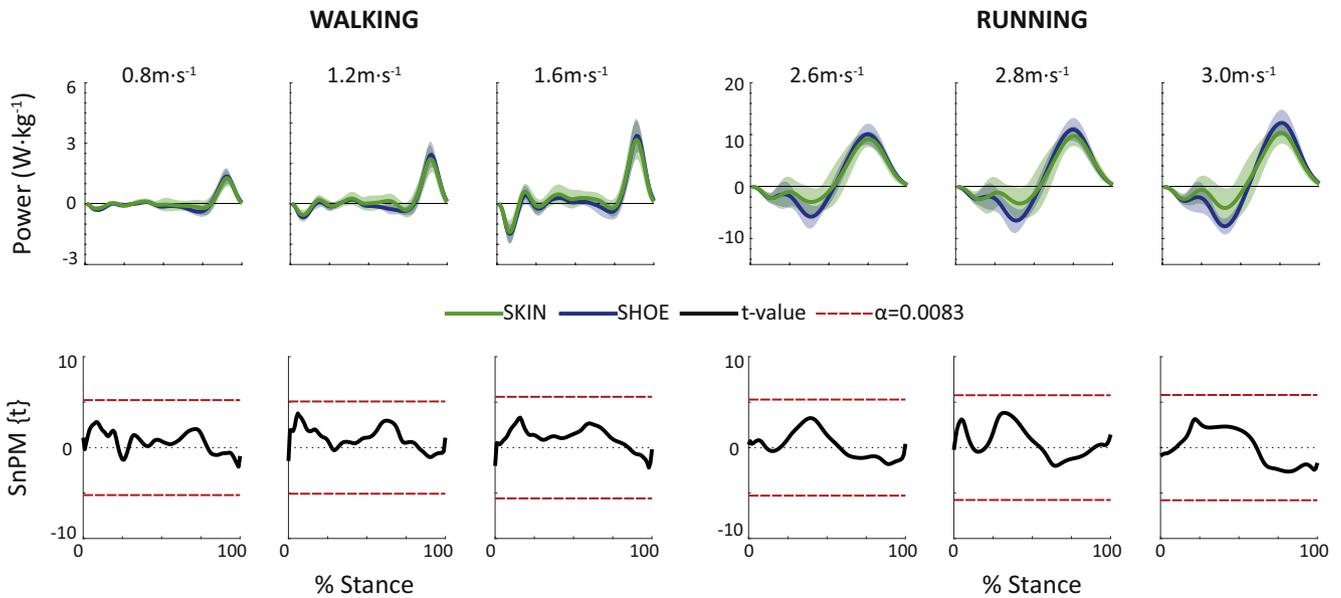
For each walking and running speed, we found that AJC power was not significantly different at any part of the gait cycle when placing the markers in the SKIN vs. SHOE configuration (Figs. 2 and 3). AJC power changed significantly with walking and running speed ( $p < 0.05$ ), but there was no interaction effect between speed and marker configuration (Fig. 2).

### 3.2. SHOE vs. SHOE<sub>alt</sub>

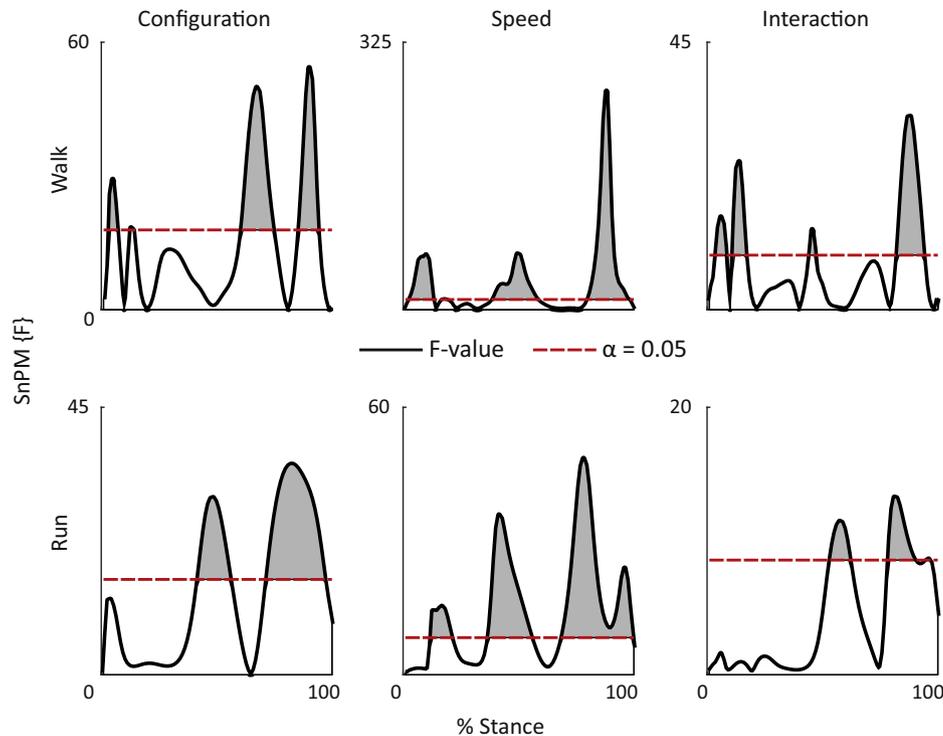
The AJC power curve did exhibit significant differences, especially during Push-off (peak positive power), when comparing the SHOE vs. SHOE<sub>alt</sub> marker configuration ( $p < 0.05$ ; Fig. 4). AJC power also changed significantly with walking and running speed ( $p < 0.05$ ; Fig. 4), and we observed a significant interaction effect between speed and marker configuration ( $p < 0.05$ ; Fig. 4). For example, at the two higher walking speeds we observed significant differences in the Preload phase (negative power region prior to Push-off), whereas these differences did not reach the level of significance during the Preload phase of the slowest speed (Fig. 5).



**Fig. 2.** SKIN vs. SHOE: two-way analysis of variance results for ankle joint complex power. The two factors presented are marker configuration, i.e., when markers were placed directly on the foot (SKIN) vs. in the same location on the shoe (SHOE) and gait speed. Statistical non-parametric mapping (SnPM) F-values (black solid line) are displayed, with alpha level threshold (red dashed line) crossings shaded grey where applicable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 3.** SKIN vs. SHOE: ankle joint complex power estimates for walking and running, computed between the shank and calcaneus using two calcaneal tracking marker set configurations captured in separate trials to maintain near-identical marker locations. Configurations were (1) a foot-mounted marker set (SKIN; light green line) and (2) a shoe-mounted marker set (SHOE; dark blue line). Data are presented as mean  $\pm$  s.d. (shaded regions), beginning at initial foot contact and ending at toe-off. Statistical non-parametric (SnPM) mapping t-values (black solid line) are displayed in lower plots, with adjusted alpha level threshold (0.05/6; red dashed line). These data are a visual tool only (post hoc testing was not required given the lack of an interaction or configuration effect). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

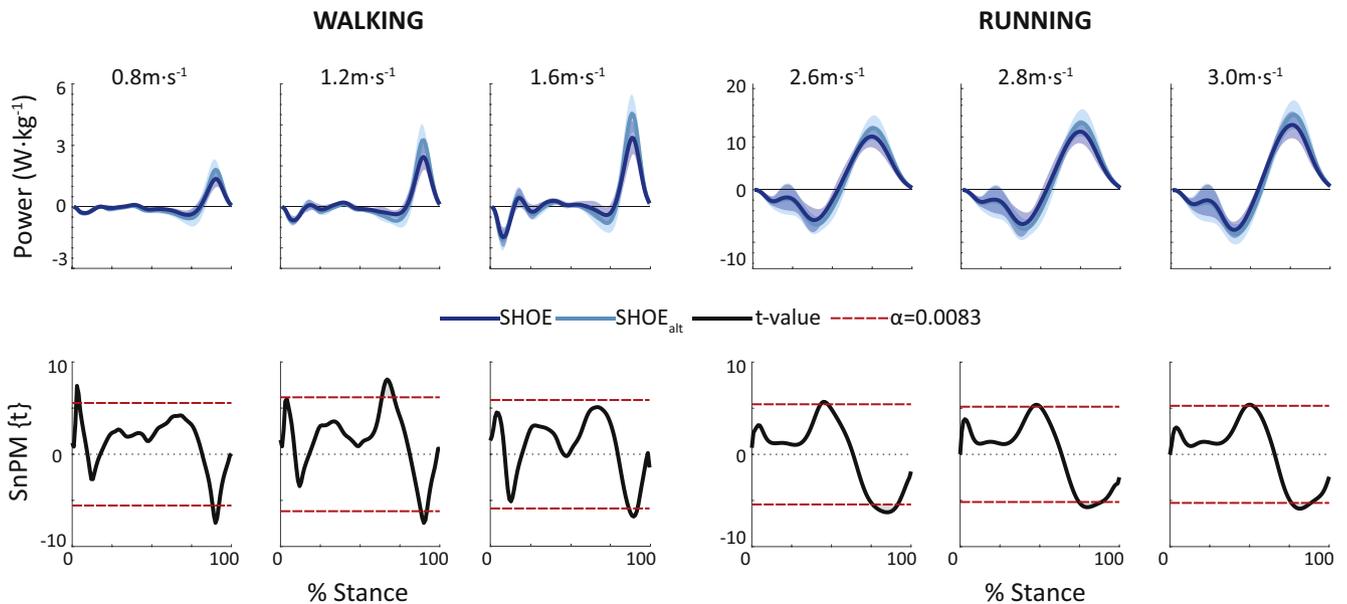


**Fig. 4.** SHOE vs. SHOE<sub>alt</sub>: two-way analysis of variance results for ankle joint complex power. The two factors presented are marker configuration, i.e., when markers are placed in two different locations on the shoe (SHOE vs. SHOE<sub>alt</sub>) and gait speed. Statistical non-parametric mapping (SnPM) F-values (black solid line) are displayed, with alpha level threshold (red dashed line) crossings shaded grey where applicable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

#### 4. Discussion

It is common for biomechanists, clinical researchers, sport scientists, rehabilitation engineers, roboticists and other human movement specialists to seek a greater understanding of biological joint function by computing joint kinetics (e.g., powers), and by

assessing continuous time-series data as opposed to only evaluating results at discrete time-points (e.g., peaks). Here, we provide data to assist researchers in answering two key questions with respect to computing AJC (shank-calcaneus) power estimates in walking and running: i) Should I cut holes in footwear to track skin-mounted foot markers or will shoe-mounted markers suffice?



**Fig. 5.** SHOE vs. SHOE<sub>alt</sub>: ankle joint complex power estimates for walking and running, computed between the shank and calcaneus using two shoe-applied calcaneal tracking marker set configurations captured in the same trial: SHOE (dark blue line) and SHOE<sub>alt</sub> (light blue line). Data are presented as mean  $\pm$  s.d. (shaded regions), beginning at initial foot contact and ending at toe-off. Statistical non-parametric (SnPM) mapping t-values (black solid line) are displayed in lower plots, with adjusted alpha level threshold (0.05/6; red dashed line) crossings shaded grey where applicable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ii) Should I tightly control calcaneal tracking marker locations between footwear conditions and/or subjects? We discovered that placing foot markers on the shoe vs. on the skin had little effect on AJC power estimates over a range of walking and running speeds. However, we identified significant differences when shoe-mounted calcaneal marker placement was varied, which may be particularly relevant to repeated-measures study designs (e.g., studies in which subjects don multiple pairs of footwear during a single test or complete multiple data collection sessions requiring the reapplication of calcaneal markers).

#### 4.1. Should holes be cut in footwear material to allow tracking of skin-mounted calcaneal markers?

The results of this study suggest that, for a group-level analysis, cutting holes was not necessary. No significant differences were observed in AJC power when comparing SKIN vs. SHOE configurations via paired t-tests (Figs. 2 and 3). This may seem somewhat counter-intuitive in light of prior studies; however, the majority of studies contrasting a skin- and shoe-mounted marker set only reported kinematic variables during high-impact movement tasks (e.g., running, side-stepping; Alcantara et al., 2018; Arnold and Bishop, 2012; Reinschmidt et al., 1992; Trudeau et al., 2017; van Gheluwe et al., 1995). Moreover, some studies collected skin- and shoe-mounted marker data in the same trial and therefore identical marker locations were not maintained between these configurations (Alcantara et al., 2018; Reinschmidt et al., 1992; Trudeau et al., 2017; van Gheluwe et al., 1995), which may have also confounded the results based on the effect of changing marker location, as described below and depicted in Fig. 5.

#### 4.2. Should calcaneal marker location be tightly controlled across subjects, footwear and testing sessions?

Ideally, marker placement should be well controlled across subjects, footwear and testing sessions. Moving each shoe-mounted calcaneal marker  $\sim$ 27 mm down significantly affected AJC power

estimates; more so than we had anticipated. The SHOE and SHOE<sub>alt</sub> derived power curves varied at peak Push-off for each walking speed, and for each running speed this occur at either peak Push-off (2.8 m·s<sup>-1</sup>) or slightly after (2.6 and 3.0 m·s<sup>-1</sup>; Fig. 5). This finding is particularly noteworthy given the popularity of peak positive power and Push-off work estimates in movement analysis studies. The observed discrepancies between SHOE vs. SHOE<sub>alt</sub> configurations were primarily due to differences in joint angle (and angular velocity), as opposed to net joint moments (see Supplementary Material), which are minimally affected by segmental motion tracking and are principally determined by the GRF vector and center of pressure.

These findings may be of high relevance to researchers employing repeated-measures study designs. If the same participant is to return for multiple data collections, then our current findings suggest that maintaining shod marker placements is an important study design consideration to avoid skewing comparisons. Precise marker placement (i.e., placing markers in the same location on each shoe) is also potentially an important consideration when participants are required to change footwear during a single session. Researchers may want to consider measuring marker distances from the sole/cushioning, or using a template to consistently place markers on the shoes.

#### 4.3. Limitations and experimental considerations

The results discussed above are applicable to walking and running within the specified speed ranges, but may not be fully generalizable to additional gait speeds or movement tasks. We expect the results to be generalizable to similar footwear (e.g., cross-training and running shoes), but not necessarily to other types of footwear (e.g., boots, dress shoes). The conclusions drawn are with respect to group (inter-subject) analysis, though there remains variability between individuals, which may warrant further study. Also, shoe marker tracking would not be expected to represent calcaneal motions for subjects with ill-fitting shoes (e.g., substantial sliding of foot within a shoe that was too large).

In the current study, each SHOE<sub>alt</sub> marker was placed ~27 mm below its corresponding SHOE marker (Fig. 1). We cannot speculate regarding the impact of smaller movements in marker placement and recommend that future work explore the influence of marker relocation magnitudes.

It is worth noting that the fabric covers used in the SHOE condition were secured tautly to the shoe's surface and were confirmed, via high speed video, to move in conjunction with shoe motions. When tracking foot motion within a shoe, marker offsets (as used in the current study) or smaller markers (<14 mm) are generally necessary. Otherwise foot marker motions could be caused or restricted by motions of the shoe. However, there are limits to the size of hole that can be cut before the shoe's structural integrity is impaired (Arnold and Bishop, 2012; Shultz and Jenkyn, 2012).

## 5. Conclusion

The results suggest that when computing AJC power for walking and running you may want to put down the scissors (i.e., forego cutting holes in your footwear), and instead pick up a Sharpie® (pen) or use a template, to help maintain consistent marker placement across trials and conditions.

## Declaration of Competing Interest

The authors report no conflict of interest.

## Reference data

Data available in data repository Dryad at <https://doi.org/10.5281/zenodo.2616532>.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2019.05.031>.

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