



## Full length article

# The relationship between supination resistance and the kinetics and kinematics of the foot and ankle during gait

Sean McBride<sup>a,\*</sup>, Philippe Dixon<sup>b</sup>, Monique Mokha<sup>a</sup>, M. Samuel Cheng<sup>a</sup><sup>a</sup> Nova Southeastern University, Davie, FL, United States<sup>b</sup> Carré Technologies, Montreal, Canada

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## ABSTRACT

**Background:** Clinical tests of foot posture and mobility are not strongly related to the dynamic kinematics of the foot during gait. These measures may be more directly related to foot and ankle kinetics. The supination resistance test (SRT) is a clinical test that may more directly measure forces acting on the weightbearing foot to provide clinicians with insight about the loading of foot structures.

**Research Question:** What is the relationship between the SRT in relaxed calcaneal stance and in single-leg-stance and the kinetics and kinematics of the foot and ankle during gait?

**Methods:** 10 healthy adults between the ages of 18 and 65 were recruited to participate in this study. Three-dimensional motion analysis was performed using the Oxford Foot Model during gait. The results of the SRT were compared with peak midfoot and ankle joint moments, power generation and absorption, joint angles, and peak angular velocities and accelerations. Correlation coefficients were calculated to assess the strength of relationships between these variables and the SRT.

**Results:** The SRT demonstrated significant relationships with several variables. In relaxed calcaneal stance, the SRT was inversely related to maximum midfoot pronation moments ( $r = -0.51$ ), maximum midfoot plantarflexion moments ( $\rho = -0.71$ ), and peak midfoot power generation ( $r = -0.61$ ). In single-leg-stance, the SRT was significantly related to maximum midfoot plantarflexion moments ( $\rho = -0.55$ ) and peak midfoot power generation ( $r = -0.47$ ).

**Significance:** The SRT is significantly associated to several kinetic variables that quantify midfoot loading during gait. Interventions that decrease supination resistance may have the potential to increase midfoot power generation.

## 1. Introduction

Foot and ankle pain is common, with up to 24% of the population experiencing frequent foot pain [1]. The costs associated with foot and ankle injuries is substantial. In 2011, Medicare incurred an estimated \$11 billion in direct and indirect costs for ankle and foot conditions [2]. This information highlights the need for a more complete understanding of foot function to guide assessment and treatment of foot dysfunction. It is also important that measures of foot function are translatable to clinical practice.

In clinical practice, static measures of foot posture and mobility are widely used. However, these measures have not been shown to be strongly associated with dynamic foot kinematics [3] and their relationship to injury is unclear. Some studies have found that a more pronated foot is a risk factor [4–6], whereas others have not [7–9]. Neal

et al. [10] found that static foot posture was associated with the development of medial tibial stress syndrome and patellofemoral pain, with pooled standardized mean differences of .28 and .32, respectively. However, these standardized mean differences are small, indicating that additional factors beyond foot posture and kinematics may be at play.

Recent work has shown that measures of foot posture and mobility using the arch height index and foot mobility magnitude were associated with kinetic variables during gait and not kinematics [11]. Low-arched, mobile feet were found to be associated with increased subtalar joint (STJ) supination moments, STJ negative work, and medial longitudinal arch (MLA) compression [11]. A net joint moment is the sum of moments produced across a joint by muscles, tendons, ligaments, and other soft tissues [12]. Negative work, represented by negative joint power, is associated with the absorption of energy and soft tissue

\* Corresponding author.

E-mail address: [mcbride.p.sean@gmail.com](mailto:mcbride.p.sean@gmail.com) (S. McBride).

deformation. These kinetic measures are thought to be indicative of soft tissue loading and may provide treatment targets for clinicians. For example, one effect of foot orthoses has been found to be a reduction in ankle inversion moments [13] while exercises targeted to the plantar intrinsic musculature of the foot may assist in reducing MLA deformation [14].

The supination resistance test (SRT) is a more direct measurement of forces acting on the foot that is thought to be related to inversion moments and midfoot mobility. The SRT was first described by Kirby and Green in 1992 to estimate of the amount of force pronating the foot in standing [15]. The test was originally performed manually, with the examiner using two fingers to apply a lifting force to the inferior aspect of the navicular with the subject in the relaxed calcaneal stance position (RCSP). The lifting force is applied until the calcaneus begins to invert and is thought to reflect the amount of force that the posterior tibialis would be required to overcome to initiate STJ supination.

Over time, several devices have been developed to measure supination resistance (SR) objectively [16,17]. The primary investigator of the current study (SM) has investigated the intra-rater reliability of SR measurements in RCSP and single-leg-stance (SLS) with a portable, handheld device that is clinically accessible and found excellent reliability (ICC = 0.90 - 0.92) in a pilot study [18].

The purpose of this study is to quantify the relationship between SR and dynamic foot function during gait. Primary variables of interest include peak midfoot and ankle joint moments as well as peak midfoot and ankle joint power generation and absorption. Secondary variables include peak midfoot and ankle joint angles in addition to peak midfoot and ankle joint angular velocity and angular acceleration. We hypothesize that (1) the SRT will demonstrate a significant positive correlation with peak ankle inversion moments and (2) a significant negative correlation with peak midfoot pronation moments, as previous research has demonstrated a pronation moment during midfoot supination in late stance [19].

## 2. Methods

### 2.1. Subjects

Ten healthy subjects ( $29.9 \pm 13.8$  years,  $166.5 \pm 9.6$  cm, and  $65.6 \pm 14.1$  kg) between the ages of 18 and 65 without history of lower extremity surgery walked barefoot at their comfortable walking speed. All subjects signed a consent form that was approved by the Internal Review Board at Nova Southeastern University. Optical markers were placed on bony landmarks in accordance with the Oxford Foot Model (OFM) (Vicon, Oxford Metrics, UK) [20].

### 2.2. Data collection and processing

A ten-camera motion capture system (Vicon Motion Systems, Centennial, CO, USA) was used to collect kinematic data at 100 Hz. Subjects walked across a walkway with an embedded force plate (Bertec, Inc., Model 4060-15, Columbus, OH, USA) that sampled data at 1000 Hz. Five walking trials consisting of a complete foot strike on the force plate for each lower extremity were collected for data analysis. Trials were labelled and the OFM was run in Vicon Nexus version 2.7.0 before the data were imported into Matlab (R2015a, The Mathworks, Inc., Natick, MA, USA) and further processed within the biomechZoo toolbox [21]. Data were filtered with a 4th order, low-pass Butterworth filter. Kinematic data were calculated for the OFM ankle joint (hindfoot with respect to the tibia) and midfoot (forefoot with respect to the hindfoot).

### 2.3. Inverse dynamic analysis

The OFM is a four-segment representation of the lower limb that includes three rigid foot segments and a rigid tibial segment. The foot



Fig. 1. The SRT performed in the RCSP. The examiner pulls vertically until the calcaneus begins to invert.

consists of a hindfoot, a forefoot, and a hallux [20]. The inverse dynamic analysis approach combines ground reaction forces with anthropometric measurements and kinematic data to obtain kinetics. For midfoot kinetics, data were analyzed after heel rise to ensure that ground-foot contact occurred at the forefoot. As done previously [19], midfoot kinetics were plotted after 60% stance. Visual inspection of the vertical position of the heel marker revealed that peak midfoot moments and power generation occurred after heel rise.

### 2.4. Supination resistance

Measurements of supination resistance were recorded with the Keystone device (Interpod, Brighton, Australia) in RCSP and single-leg-stance (SLS) (Fig. 1). The Keystone consists of a handheld scale from which a 25 mm-wide non-stretchable strap is fixed. The strap passes under the foot from just medial to the navicular tuberosity to the calcaneocuboid region laterally, where it attaches to an anchor that abuts the foot and rests on the floor. The primary investigator (SM) instructed the subject to march in place for 5 steps before coming to RCSP. The subject then lifted the heel of the foot to be tested and the strap was placed under the foot as described. The subject was instructed to look straight ahead and to neither assist nor resist the pull of the strap.

SR was measured by pulling vertically on the strap until a vertical line bisecting the posterior calcaneus demonstrated inversion motion. The average of five measurements was used for data analysis. Output, measured in pounds, was converted to Newtons. For measurements in SLS, the same general procedure was followed except subjects stood in a doorway on the foot to be tested with their index and middle fingers on the door frame for support.

### 2.5. Statistical analysis

Midfoot and ankle joint peak internal joint moments (Nmm/kg), power (W/kg), peak segment angles (degrees) in all three planes (x, y, z corresponding to sagittal, frontal, and transverse planes, respectively), and peak midfoot and ankle joint angular velocity (rad/s) and angular acceleration (rad/s<sup>2</sup>) were analyzed and compared with the SRT (N) in RCSP and SLS. Pearson correlation coefficients were calculated to assess the relationship between variables. Normality was assessed with the Shapiro-Wilk test in R version 3.3.2. Variables demonstrating suspected deviations from normality are identified in Tables 1–3. Spearman correlation coefficients were calculated for comparisons between non-

**Table 1**  
Midfoot and ankle joint kinematics.

Angles	Degrees	Correlation with SRT RCSP		Correlation with SRT SLS		
		r/rho	p value	r/rho	p value	
FF/HF <sub>x</sub>	Max	9.8 (3.3)	0.03	0.91	0.29	0.22
	Min	-5.7 (4.5)	0.26	0.27	0.42	0.07
FF/HF <sub>y</sub>	Max	9.0 (4.4)	-0.21	0.37	-0.02	0.94
	Min	2.8 (4.4)	-0.23	0.33	0.05	0.83
FF/HF <sub>z</sub>	Max	7.9 (3.7)	-0.01	0.98	-0.12	0.61
	Min	0.8 (3.4)	0.10	0.68	-0.04	0.88
AnkleAngle <sub>x</sub>	Max	7.6 (3.0)	-0.23	0.33	-0.39	0.09
	Min	-12.9 (3.5)	0.07	0.76	-0.08	0.75
AnkleAngle <sub>y</sub>	Max	7.7 (2.8)	0.27	0.26	0.18	0.44
	Min	-7.0 (2.9)	0.44	.052	0.29	0.22
AnkleAngle <sub>z</sub>	Max	6.3 (7.1)	-0.27	0.24	-0.04	0.87
	Min	-10.3 (8.2)	-0.42	0.07	-0.05	0.85

FF/HF: forefoot relative to hindfoot; SRT: supination resistance test; RCSP: relaxed calcaneal stance position; SLS: single-leg-stance; FFHF: forefoot relative to hindfoot.

normal variables. The alpha value for statistical significance was 0.05. Correlation coefficients as well as descriptive statistics were calculated with JASP Version 0.9.2 (JASP Team (2018). JASP (Version 0.9). The following interpretations of correlation coefficients were made: coefficients less than 0.25 demonstrated little to no relationship, those between 0.25 and 0.50 revealed a fair relationship, a moderate to good relationship existed between 0.50 to 0.75, and an excellent relationship occurred with coefficients greater than 0.75 [22].

**3. Results**

The mean (SD) for SR measurements was 86.4 N (17.4) in RCSP and 136.1 N (18.5) in SLS. Mean maximum and minimum joint angles for the forefoot with respect to hindfoot (FF/HF) and the ankle along with net internal joint moments are presented in Tables 1 and 2, respectively. Maximum and minimum segmental angular velocities and angular accelerations of the forefoot and hindfoot are presented in Table 3. Midfoot and ankle kinematics and kinetics are depicted in Figs. 2 and 3, respectively. Scatter plots depicting the relationship between the SRT in RCSP and several kinetic variables are included in Figs. 2 and 3.

**Table 2**  
Midfoot and ankle joint kinetics.

Net Internal Moment		N mm/kg	Correlation with SRT RCSP		Correlation with SRT SLS	
			r/rho	p value	r/rho	p value
MidFootMoment <sub>x</sub>	Max	136.1 (55)	-0.71 <sup>#</sup>	< 0.001 <sup>*</sup>	-0.55 <sup>#</sup>	0.01 <sup>*</sup>
MidFootMoment <sub>y</sub>	Max	56.3 (19.3)	-0.51	0.02 <sup>*</sup>	-0.20	0.40
MidFootMoment <sub>z</sub>	Max	86.9 (79.5)	-0.17 <sup>#</sup>	0.47	0.19 <sup>#</sup>	0.43
AnkleMoment <sub>x</sub>	Max	1413 (122.1)	0.16	0.50	0.002	0.99
	Min	-122.2 (43.3)	0.41	0.08	0.24	0.31
AnkleMoment <sub>y</sub>	Max	109.7 (54.9)	0.13	0.60	0.004	0.99
	Min	-33.4 (27.8)	-0.19 <sup>#</sup>	0.43	-0.27 <sup>#</sup>	0.26
AnkleMoment <sub>z</sub>	Max	109.8 (65.4)	-0.21	0.38	0.05	0.82
	Min	-58.1 (44.1)	-0.04	0.86	0.18	0.45

Joint Power		W/kg	Correlation with SRT RCSP		Correlation with SRT SLS	
			r/rho	p value	r/rho	p value
MidFoot generation	Max	1.7	-0.61	0.005 <sup>*</sup>	-0.47	0.04 <sup>*</sup>
Ankle generation	Max	1.9	-0.20	0.40	-0.07	0.76
Ankle absorption	Max	-0.56	0.19	0.42	0.20	0.39

SRT: supination resistance test; RCSP: relaxed calcaneal stance position; SLS: single-leg-stance.

\* Indicates statistically significant relationship at alpha level of 0.05.

# Indicates use of Spearman rho due to suspected deviation from normality.

For the variables related to the hypotheses, SR in RCSP was not associated with peak AnkleMoment<sub>y</sub> (r = 0.13, p = 0.60) but did demonstrate a significant inverse relationship with peak MidfootMoment<sub>y</sub> (r = -0.51, p = 0.02). In SLS, SR was neither significantly related with peak AnkleMoment<sub>y</sub> (r = 0.004, p = 0.99) nor peak MidfootMoment<sub>y</sub> (r = -0.20, p = 0.40). Tables 1–3 contain the results of all comparison tests made in our analysis.

**4. Discussion**

Part one of the hypothesis that a significant positive association between the SRT and peak ankle inversion moments exists was not demonstrated in this study. However, our hypothesis that the SRT would be inversely related to midfoot pronation moments was substantiated. Furthermore, several moderate to good relationships with other midfoot kinetic variables and with angular velocities and accelerations of the forefoot and hindfoot were discovered. With the increased use of multi-segment foot models, there is a growing body of research underscoring significant contributions of the midfoot to foot function during gait [19,23]. We suspect that the inverse relationship between the SRT in RCSP and midfoot pronation moments occurs because the SRT measures the ability of the forefoot to supinate on the hindfoot. As less force is needed for forefoot supination to occur, greater control may be required from the midfoot pronators to coordinate the amount of supination that takes place in late stance.

Although our hypotheses related to frontal plane midfoot and ankle joint moments, our results reveal greater relationships between the SRT in RCSP and peak midfoot plantarflexion moments (rho = -0.71, p < 0.001) and peak midfoot power generation (-0.61, p = 0.005). It is possible that alternative devices for the measurement of SR may provide results that are more reflective of frontal plane moments. Griffiths and McEwan created a computerized lever device to mimic the original SRT [16]. When pulled by the examiner, the lever caused a metal “finger” placed beneath the navicular to raise vertically until subtalar joint supination was observed. Unfortunately, the size and cost of the device would be prohibitive for routine clinical use. Another potential solution may be to use a device like that of Payne et al. [17] which also uses a strap, but with an anchor that is fixed to the standing platform instead of resting against the lateral foot. It is possible that the anchor of the device we used is pulled medially toward the lateral foot causing a doming of the midfoot in the sagittal plane.

Testing of the SRT in SLS is thought to better reflect the forces acting

**Table 3**  
Forefoot and hindfoot angular velocities and accelerations.

Angular Velocity		rad/s	Correlation with SRT RCSP		Correlation with SRT SLS	
			r/rho	p value	r/rho	p value
ForeFootVel <sub>x</sub>	Max	1.68 (2.78)	−0.08 <sup>#</sup>	0.75	0.09 <sup>#</sup>	0.71
	Min	−8.91 (1.51)	−0.51	0.02 <sup>*</sup>	−0.25	0.29
ForeFootVel <sub>y</sub>	Max	7.03 (5.18)	−0.34 <sup>#</sup>	0.15	−0.30 <sup>#</sup>	0.20
	Min	−2.59 (1.62)	0.08 <sup>#</sup>	0.74	0.23 <sup>#</sup>	0.34
ForeFootVel <sub>z</sub>	Max	5.24 (3.37)	−0.13 <sup>#</sup>	0.59	−0.20 <sup>#</sup>	0.39
	Min	−1.98 (2.17)	0.03 <sup>#</sup>	0.92	0.18 <sup>#</sup>	0.44
HindFootVel <sub>x</sub>	Max	0.12 (0.16)	−0.56	0.01 <sup>*</sup>	−0.53	0.02 <sup>*</sup>
	Min	−6.36 (1.15)	0.47	0.04 <sup>*</sup>	0.40	0.08
HindFootVel <sub>y</sub>	Max	3.59 (4.24)	−0.44 <sup>#</sup>	0.051	−0.05 <sup>#</sup>	0.83
	Min	−1.40 (0.70)	0.20	0.39	0.24	0.31
HindFootVel <sub>z</sub>	Max	0.70 (0.27)	−0.52	0.02	−0.25	0.28
	Min	−1.69 (1.05)	0.18	0.45	−0.06	0.81

Angular Acceleration		rad/s <sup>2</sup>	Correlation with SRT RCSP		Correlation with SRT SLS	
			r/rho	p value	r/rho	p value
ForeFootAcc <sub>x</sub>	Max	91.1 (21.3)	−0.47	0.04 <sup>*</sup>	−0.08	0.73
	Min	−159.2 (69.5)	0.47 <sup>#</sup>	0.04 <sup>*</sup>	0.20 <sup>#</sup>	0.40
ForeFootAcc <sub>y</sub>	Max	4.24 (4.92)	−0.55 <sup>#</sup>	0.01 <sup>*</sup>	−0.31 <sup>#</sup>	0.19
	Min	−171.8 (162)	0.13 <sup>#</sup>	0.58	0.23 <sup>#</sup>	0.34
ForeFootAcc <sub>z</sub>	Max	172.7 (194.6)	0.01 <sup>#</sup>	0.97	−0.08 <sup>#</sup>	0.73
	Min	−132.2 (136.3)	−0.02 <sup>#</sup>	0.93	0.11 <sup>#</sup>	0.65
HindFootAcc <sub>x</sub>	Max	96.7 (33.3)	−0.55 <sup>#</sup>	0.01 <sup>*</sup>	−0.27 <sup>#</sup>	0.25
	Min	−64.1 (21.7)	0.51	0.02	0.30	0.21
HindFootAcc <sub>y</sub>	Max	83.11 (103.0)	−0.40 <sup>#</sup>	0.08	−0.09 <sup>#</sup>	0.71
	Min	−33.9 (16.3)	0.14	0.57	0.28	0.24
HindFootAcc <sub>z</sub>	Max	13.9 (5.8)	−0.04	0.87	−0.02	0.95
	Min	−32.7 (16.6)	0.42 <sup>#</sup>	0.06	0.16 <sup>#</sup>	0.51

SRT: supination resistance test; RCSP: relaxed calcaneal stance position; SLS: single-leg-stance.

\* Indicates statistically significant relationship at alpha level of 0.05.

# Indicates use of Spearman rho due to suspected deviation from normality.

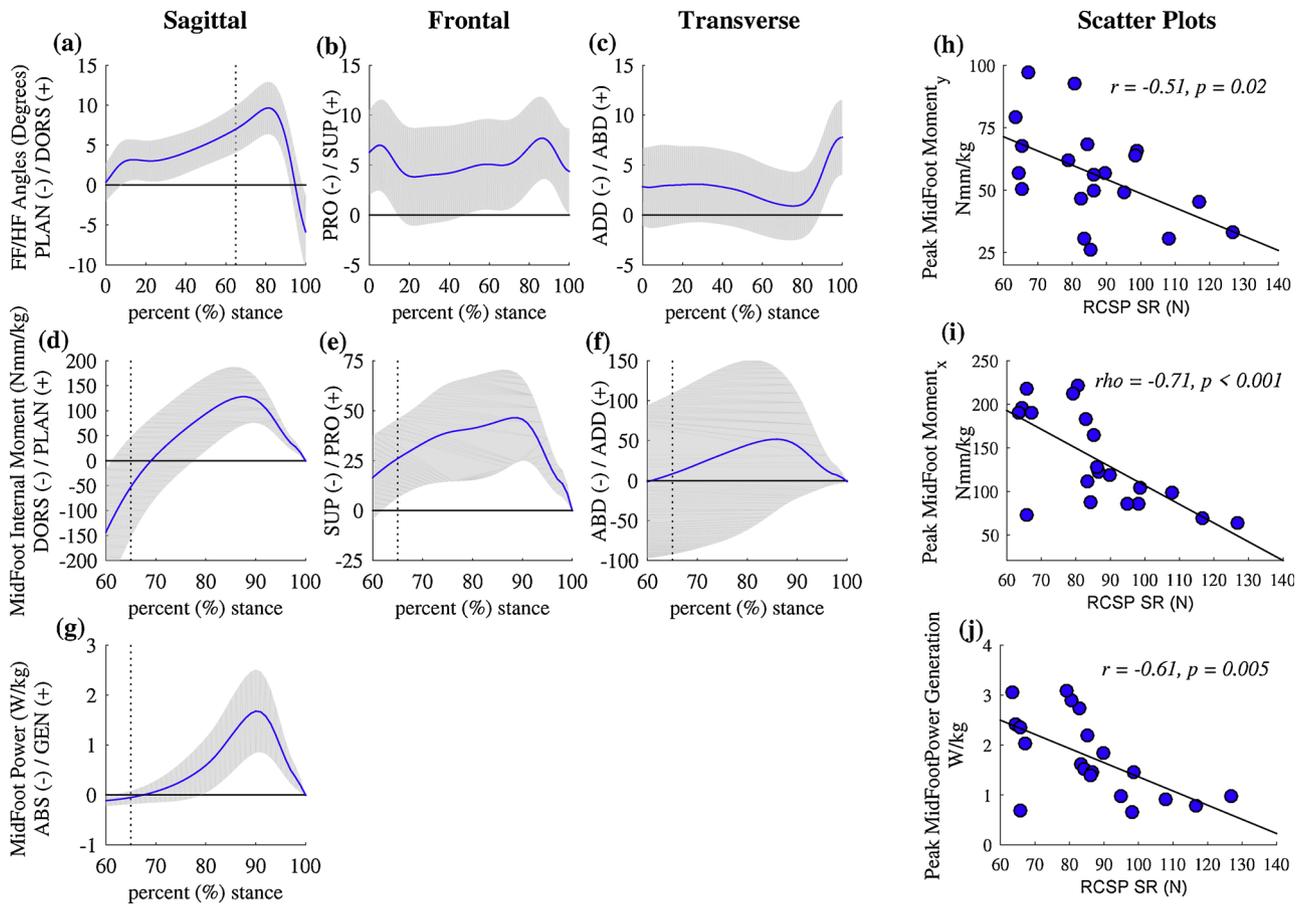
on the foot during the stance phase of gait. However, measurements of SR in SLS provided less desirable correlations with the gait parameters under investigation in this study. The magnitude of the relationship with peak midfoot pronation moments became insignificant in SLS, decreasing to  $r = -0.20$ . Similarly, associations with peak midfoot plantarflexion moments and peak midfoot power generation decreased to  $\rho = -0.55$  from  $\rho = -0.7$  and from  $r = -0.61$  to  $r = -0.47$ , respectively. Several limitations exist to testing in SLS, including the increased force required from the examiner and the increased lower limb muscular activity of the subjects as they must maintain stability. Furthermore, the Keystone must be held at a stable force before an output from the device is recorded. This delay may take several seconds and might result in less than optimal results as the examiner attempts to maintain the device steady.

OFM kinematic and kinetic values from this study are in line with others that assessed healthy participants [19,24,25]. While many studies have presented kinematic data, far fewer report kinetics. Dixon et al. [19] calculated midfoot and ankle joint moments after heel rise in adolescents. Our peak midfoot and ankle joint kinetics are similar, except that our participants demonstrated higher peak midfoot power of 1.7 W/kg compared to 1.1 W/kg. For the present study, peak midfoot plantarflexion moments were 136 Nmm/kg versus 100 Nmm/kg reported by Dixon et al. [19]. This difference in midfoot plantarflexion moments in our study is likely due to the older age of our participants and may account for the increase in midfoot power generation. Diliberto et al. [23] found that midfoot power generation scales in proportion to ankle power generation during tasks of increasing demand. Although Diliberto et al. used a different multi-segment foot model, peak midfoot power increased from 0.5 W/kg while walking to 0.7 W/

kg and 1.1 W/kg while ascending a standard step and a high step, respectively [23]. These findings demonstrate the importance of midfoot power generation to gait and tasks of daily living.

We believe the SRT with the device we used may measure the ability of the midfoot to attain a position capable of transmitting increased power as the hindfoot begins to invert, with lower values of SR being associated with increased forefoot plantarflexion velocity ( $r = -0.51$ ,  $p = 0.02$ ) and midfoot power generation. This finding may be relevant to the prescription of foot orthoses. It is possible that foot orthoses that decrease SR might increase midfoot power generation. However, research is required to verify this hypothesis. Moreover, our finding may support the need for individuals with high SR to strengthen the plantar intrinsic musculature to assist with power generation.

Several fair to moderate correlations between SR and peak joint angles were also observed. Our results for kinematic variables did not reach statistical significance, which likely points to the study being underpowered to detect these effect sizes. In SLS, the correlation with the SRT and midfoot plantarflexion was  $r = 0.42$ ,  $p = .07$  and with hindfoot dorsiflexion was  $r = -0.39$ ,  $p = .09$ . In RCSP, the correlation coefficients for the SRT with peak hindfoot eversion was  $r = 0.44$ ;  $p = .052$  and with peak hindfoot external rotation  $r = -0.42$ ;  $p = .07$ . These results add to the literature that demonstrates that dynamic kinematics are more difficult to predict than kinetics. The effect sizes of our kinematic findings are also of the same magnitude of another recent study [26] that measured midfoot torque to inversion and eversion in a non-weightbearing position. Significant moderate correlations with peak forefoot inversion ( $\rho = 0.38$ ), peak forefoot dorsiflexion ( $\rho = -0.35$ ), and peak rearfoot eversion angles ( $\rho = -0.45$ ) were observed. However, no analysis of foot or ankle kinetics was carried out.



**Fig. 2.** FF/HF angles (a,b,c), midfoot moments (d,e,f), midfoot power (g) during the stance phase of gait as computed by the OFM. The blue line represents the average of all walking trials for all participants. The shaded grey area represents the standard deviation of OFM data. Vertical dashed lines represent the timing of heel rise. Scatter plots (h, i, j) demonstrating the relationship between the SRT in RCSP and midfoot kinetics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The device we utilized, while much less sophisticated, has a greater potential of applicability to the clinical setting than the one used to measure torque by Gomes et al [26].

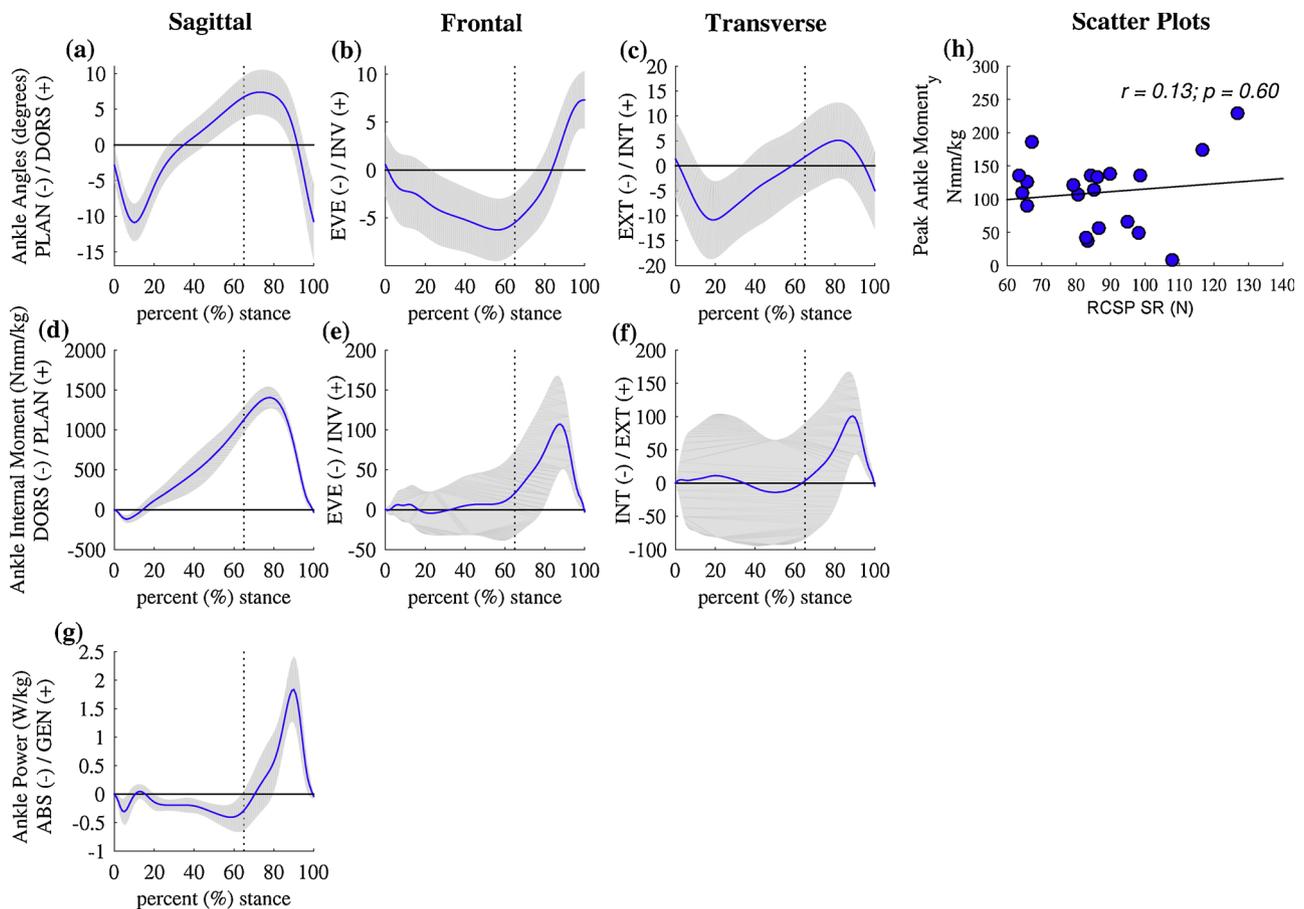
Previous studies have presented means and standard deviations for SR in RCSP, but comparisons may be hindered by differences in devices used for testing as well as participant characteristics. Our mean (SD) of 86.4 N (17.4) in RCSP is less than other studies reporting means ranging from 113.5 N (35.4) to 167 N (71.6) [16,17,27]. This difference may be partly attributable to the fact that participants in this study weighed less and demonstrated less between subject variability in SR measurements. Bodyweight was not significantly associated with SR in RCSP in this sample ( $r = .32, p = .17$ ). This suggests that bodyweight explained 10% of the variation in SR measurements while in RCSP, a finding similar to work by both Griffiths and McEwan [16] and Noakes and Payne [17]. In one study, Payne et al [27] found that bodyweight accounted for 27% of the variability in SR. To our knowledge, we are the first to report measurements of SR in SLS. In SLS, bodyweight was significantly associated with SR,  $r = 0.66; p = .002$ . Thus, the contribution bodyweight to SR increased to 43% in SLS. Participant age was also not related to SR in RCSP ( $\rho = -0.04, p = 0.87$ ) or in SLS ( $\rho = 0.06, p = 0.78$ ).

There are several limitations to our study. The OFM does not directly track the motion of any midfoot bones. Instead, relative motion of the forefoot with respect to the hindfoot serves as the midfoot segment

[20]. This simplification likely leads to less accurate calculations of midfoot kinetics and kinematics when compared to other models. However, the OFM is easily implemented, clinically relevant, and does not require additional pressure data or processing time. The OFM also combines the talocrural joint and the STJ to create the hindfoot segment. Consequently, the inversion and eversion moments acting at the STJ cannot be modeled. Therefore, it is not known if the SRT is related to frontal plane moments at the STJ.

Finally, the interrater reliability of the SRT with the Keystone device has not been studied, limiting the test's generalizability to other examiners. Several variables may limit interrater reliability of the test, including the speed of the pull on the device, the angle of the pull, and the examiner's judgment of when calcaneal inversion begins. Future research should examine the interrater reliability of the SRT with the Keystone device. Also, improving the testing procedure in SLS by allowing participants to better stabilize themselves may produce better results.

As tested in this study, the results of the SRT were associated with peak midfoot pronation moments, but not peak ankle inversion moments. Furthermore, moderate to good significant relationships were found with peak midfoot plantarflexion moments and midfoot power generation.



**Fig. 3.** Ankle angles (a,b,c), ankle moments (d,e,f), and ankle power (g) during the stance phase of gait as computed by the OFM. The blue line represents the average of all walking trials for all participants. The shaded grey area represents the standard deviation of OFM data. Vertical dashed lines represent the timing of heel rise. Scatter plot (h) demonstrating the relationship between the SRT in RCSP and ankle inversion moment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### CRedit authorship contribution statement

**Sean McBride:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing - original draft, Project administration. **Philippe Dixon:** Data curation, Software, Visualization, Writing - review & editing. **Monique Mokha:** Software, Investigation, Resources, Supervision, Writing - review & editing, Project administration. **M. Samuel Cheng:** Conceptualization, Methodology, Resources, Supervision.

### Declaration of Competing Interest

The authors of this study declare no conflict of interest financially or otherwise with any other parties.

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