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Research Article

Arch Height Mediation of Obesity-Related Walking in Adults: Contributors to Physical Activity Limitations

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Walking and foot arch structure have risk-increasing effects that contribute to decreased physical activity in adults with overweight and obese body mass index (BMI) scores. However, it is unknown whether both excessive weight and arch height influence walking compared to the effects of excessive weight or arch height alone. The purpose of this study was to investigate if arch height mediates obesity-related walking characteristics among adults with different BMI classifications. Spatiotemporal walking kinematics and dynamic plantar pressure were collected as adults with normal ($n = 30$), overweight ($n = 34$), and obese ($n = 25$) BMI scores walked at their preferred speed. Digital footprints created with plantar pressure data were used to calculate a measure of arch height, the Chippaux-Smirak Index (CSI). The results showed that obese adults had lower arches than normal weight adults ($P < 0.05$). Arch height was related to velocity, double limb support time, stance time, step length, and foot rotation (all $Ps < 0.05$). Overweight participants with lower arches had lower velocities and higher double limb support times (all $Ps < 0.05$). The results have implications for aiding an increase in physical activity for overweight adults via intervening in adults' arch height.

1. Introduction

Obesity is a major public health concern worldwide. The prevalence of being overweight or obese is high; more than 1.4 billion adults (35%) in the world over 20 years old are overweight and 11% are obese [1]. To combat obesity, increased energy expenditure with more physical activity has been recommended for overweight and obese adults; physical activity promotes weight loss, prevents weight gain, and can help maintain good metabolic health [2]. Walking is a common and cost effective intervention used to increase overall physical activity [3] and to meet the recommended 150 minutes of weekly moderate-to-vigorous physical activity [2]. However, overweight and obese adults fall short of these recommendations [4].

A possible contributor to decreased physical activity via walking is the risk-increasing effect that body mass index (BMI) has on walking [5, 6] and plantar pressure [7, 8]. Walking is a rhythmical, cyclical activity, but requires coordinating motor actions specific to constraints [9–11] such as body weight. Compared to adults with normal weight, adults who are classified as overweight or obese show differences in spatiotemporal gait parameters. They take shorter steps by decreasing step and stride length, walk more slowly by decreasing velocity, and spend more time with their feet on the ground by decreasing swing time as well as increasing double limb support and stance time during overground walking [5, 6]. Obesity has effects on the biomechanics and bioenergetics of walking in adults. Overweight and obese adults demonstrate modifications in

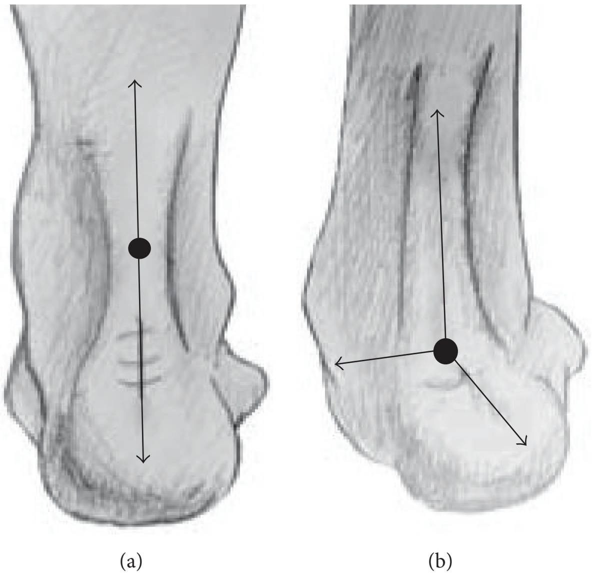
(a) (b)

Figure 1: Right foot that is in a neutral position (a) compared to a right foot that is excessively pronated (b). The middle arrow on the foot that is excessively pronated depicts the inward (i.e., pronated) position of the foot.

gait at the ankle, knee, and hip such as reduced range of motion [12]. When walking faster than their preferred speed, these adults also have greater absolute ground reaction forces [13] and increased load at the knee [14] compared to normal-weight adults. These differences in walking, especially slower preferred walking speed, are attributed to overweight and obese adults' attempt to increase stability because of impaired balance [15], to minimize mechanical external work [16], to decrease load at the knee [17], and to curb energy cost and relative effort [13]. However, the differences in walking are actually associated with increased safety risks such as tripping [18]. Overweight and obese adults also tend to have lower arches or "flat feet" during stance based on footprint and plantar pressure measures [7, 8, 19]. Their feet tend to be more flexible during the propulsive phase of walking [20, 21]. Individuals with lower arches based on weight bearing static measurements are sometimes characterized as exhibiting a phenomenon known as excessive foot pronation during standing (Figure 1). Data on static weight bearing foot position in obese adults suggests that those with pronated feet in standing are more likely to develop foot pain [22] such as chronic plantar heel pain [23]. The combination of differences in walking and arch height in overweight and obese adults is thought to contribute to musculoskeletal injuries due to soft tissue damage [24] such as posterior tibial tendon dysfunction [25], ankle sprains [5], and plantar fasciitis [26].

Although both walking parameters and arch height have been shown to differ in overweight and obese adults and to contribute to their increased injury risks, to our knowledge, no studies have examined the relationship between walking and arch height in these populations. That is, we have no knowledge to confirm whether both excessive weight and low arches together result in altered walking compared to the effects of either excessive weight or low arch height alone. Anthropometrics contribute to obesity-related walking characteristics [5], but only the effects of some weight-related anthropometrics have been examined. The purpose of the current study is to examine whether arch height mediates obesity-related changes in walking using basic, standard spatiotemporal gait measures. We hypothesized that (1) BMI would be correlated with arch height so that individuals with higher BMI scores would have lower arches and that (2) arch height would mediate walking characteristics in overweight and obese adults as measured by spatiotemporal gait parameters.

2. Method

2.1. Participants. Participants were recruited and tested at the Living Laboratory in the Boston Museum of Science and in the *Motor Development and Human Adaptation Laboratories* at Boston University. As in previous gait studies [5] BMI was used to determine body mass classification. We derived BMI classifications from measures of BMI scores (i.e., weight in kg/height in m^2) [28]. BMI scores $\geq 19\,\text{kg/m}^2$ and $<25\,\text{kg/m}^2$ were categorized as normal weight, $\geq 25\,\text{kg/m}^2$ and $<30\,\text{kg/m}^2$ were considered to be overweight, and $\geq 30\,\text{kg/m}^2$ were deemed to be obese. Eighty-nine adults in three BMI classification groups participated: 34 with overweight BMI, 25 with obese BMI, and 30 with normal BMI. Table 1 includes demographic information and anthropometric characteristics for each group. Participants had no known significant injuries affecting their gait or safe participation in the study such as foot deformities, orthopedic injuries, or cardiac, visual, hearing, and neuropathic conditions. The study was approved by the Boston University and the Boston Museum of Science Institutional Review Boards and conformed to the Declaration of Helsinki. Informed written and verbal consent was obtained from all participants before testing began.

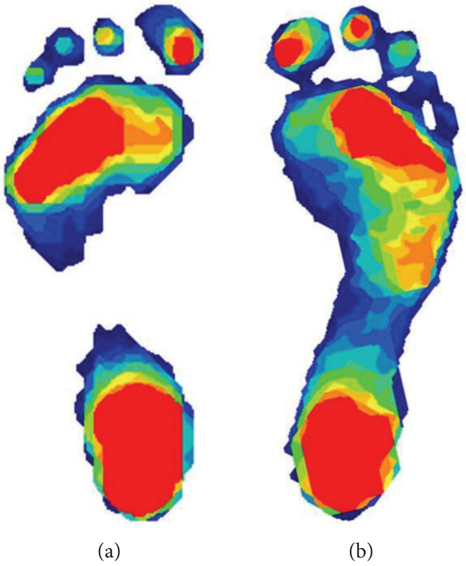

Figure 2: Example of digital footprint data collected with the high resolution (HR) Mat VersaTek. These feet represent two participants: one with a higher arch (a) and one with a lower arch (b). Note that the white space in the center of the foot on the left is representative of a higher arch since that part of the foot does not touch the mat. The colors indicate areas of the feet that exert pressure that is graded from low (blue) to high (red) areas of pressure in kilopascals. The high-arched individual on the left is a 40-year-old male with a BMI of 26.35 kg/m^2. The low-arched individual on the right is male, 46 years old, and has a BMI of 36.86 kg/m^2.

Table 1: Demographics by BMI classification. Means with standard deviations in parentheses.

	Normal weight	Overweight	Obese
BMI (kg/m^2)	21.81 (1.50)	26.94 (1.45)	34.80 (3.60)
Weight (kg)	63.48 (7.30)	76.37 (9.82)	100.80 (16.79)
Age (years)	37.27 (13.55)	38.74 (14.74)	38.16 (13.25)
Sex (M, F)	10 M, 20 F	10 M, 24 F	14 M, 11 F
Waist circumference (cm)	83.47 (9.40)	93.29 (14.40)	110.96 (10.58)
Leg length (cm)	91.20 (5.74)	90.08 (5.91)	90.81 (6.06)
Height (cm)	170.51 (9.09)	168.07 (8.84)	169.86 (11.06)

* M: male; F: female.

2.2. Arch Height Measures. We estimated participants' arch height using two methods: digital footprints with a plantar pressure mat and navicular height measures. First, participants' weight was obtained and used to calibrate measures for the digital pressure mat values. Second, dynamic plantar pressure was gathered via a continuous metric (i.e., plantar pressure) using a portable digital pressure mat (Tekscan Inc., South Boston, MA, http://www.tekscan.com/). The mat (488 mm × 447 mm) consists of 8,448 sensing elements (4 sensel/cm^2), which collected at 185 Hz. Third, Tekscan software was used to find the peak pressure distribution recorded at each sensor in order to create a digital footprint during walking sequences (Figure 2). Last, these digital footprints were used to estimate arch height using the Chippaux-Smirak Index (CSI) [29, 30]. The CSI is a commonly used measure of arch height [31] and is correlated with skeletal measures of arch height such as the navicular height [27, 32]. The CSI was developed by Chippaux and Smirak [32] independently and later used to quantify arch height. The CSI is the ratio between the smallest width of the mid-foot and the largest width of the metatarsal head area (i.e., ball of the foot). We also measured navicular height in a subset of participants in each BMI category to ensure that the CSI values obtained with digital footprints matched structural measures for arch height. Specifically, navicular height was measured for a subset of 18 participants with normal ($n = 7$), overweight ($n = 5$), and obese ($n = 6$) BMI scores.

2.3. Spatiotemporal Gait Measures. Spatial and temporal parameters of participants' footfalls were also collected. A portable, pressure-sensitive gait carpet (6.10 m long × 0.89 m wide) registered the x and y coordinates of every footfall in real-time with a 1.27 cm spatial resolution (GAITRite Inc., Clifton, New Jersey, http://www.gaitrite.com/). GAITRite software was used to calculate walking parameters: velocity (in cm/second for each trial), step length (distance in cm between heel contacts for contralateral limbs), cadence (steps/min), single limb support time (time from toe off to heel contact of the same limb in seconds), double limb support time (time from heel contact to toe off of contralateral limbs in seconds), stance time (time from heel contact to toe off of the same limb in seconds), step time (time from heel contact to heel contact of the contralateral limbs in seconds), swing time (time from toe off to heel contact of the same limb in seconds), and foot rotation, which is the amount of outward or inward foot orientation in degrees (i.e., "toe-ing out or toe-ing in" indicated by positive values for outward foot rotation, negative values for inward foot rotation, and zero for feet facing forward).

2.4. Procedure. Participants' weight was obtained with a digital scale. Height was measured with a tape measure attached to a wall. Weight and height were used to calculate BMI in kg/m^2 [28]. Waist circumference and limb length were measured with a tape measure. Waist circumference was measured as the midpoint between participants' last rib (i.e., nonfloating) and the top of the iliac crest. We measured the length of participants' legs using well-known bony landmarks as a guide; leg length was measured for each leg from bones at the hips (i.e., the anterior superior iliac spine) to the inner portion of the ankles (i.e., the medial malleolus). For a subset of participants ($n = 18$), the navicular bone was palpated and marked with a washable marker in standing. The height of the location for the navicular bone was then marked on an index card, which was placed on the floor flush against participants' feet. An experimenter later measured the height of the mark on the index card with a ruler.

The gait carpet and digital pressure mat were placed abutting one another to create a continuous walking path approximately 6.5 m long. Participants stood at the very beginning of the walking path and walked barefoot along the path for two trials. They were instructed to walk at their normal pace (i.e., preferred walking speed) without stopping until after the end of the path. Trials were processed using GAITRite software. Both trials were averaged for each individual for statistical analyses.

2.5. Statistical Analyses. SPSS 20.0 statistical software was used to complete all statistical analyses. The results were presented as means (M) and standard deviations (SD) and/or counts as appropriate. A partial correlation was run on navicular height and CSI controlling for BMI to examine the relationship between footprint and structural measures of arch height. Pearson's correlations were run to examine the relationship between BMI and anthropometrics, CSI, and spatiotemporal gait parameters. Separate one-way ANOVAs were conducted on anthropometric measures and on CSI with BMI classification as the independent variable to examine group differences. To investigate the relationship between CSI and gait parameters by group, ANCOVAs were run with BMI classification as the independent variable and CSI as a covariate separately for each gait parameter as the dependent variable. For all tests, statistical significance was set at 0.05 (two-tailed). We applied Bonferroni adjustments to follow up comparisons on significant group differences for anthropometrics, CSI, and relationship between CSI and velocity, double limb support time, and step width. Effect sizes for follow-up pairwise comparisons are represented with Cohen's d after each P value comparing mean differences [33]. Effect sizes can be interpreted as small, medium, or large based on absolute values of Cohen's d (i.e., Cohen's d may be a negative value, but interpreting the effect size is based on the absolute value): absolute values of Cohen's $d \geq 0.2$ = small effects, ≥ 0.5 = medium effects, and ≥ 0.8 = large effects.

3. Results

3.1. Anthropometrics. As expected, findings confirmed the relationship between anthropometric measures and BMI classification (Table 1). The results showed significant differences for waist circumference ($F(2,88) = 37.18$, $P < 0.001$) and mass ($F(2,88) = 72.37$, $P < 0.001$). Adults with obese BMI scores had higher waist circumference measures than overweight ($P < 0.01$, $d = 1.47$) and normal weight participants ($P < 0.01$, $d = 2.29$), and overweight participants had higher waist circumferences than normal weight participants ($P < 0.01$, $d = 0.82$). Results were similar for mass; participants with obese BMI scores had higher measures than overweight ($P < 0.001$, $d = 2.04$) or normal weight participants ($P < 0.001$, $d = 2.67$), and overweight participants had higher mass measures than normal weight participants ($P < 0.001$, $d = 0.92$). There were no differences in height ($F(2,88) = 0.34$, $P > 0.05$) or leg length ($F(2,88) = 0.30$, $P > 0.05$) based on weight classification.

3.2. BMI Classification and Arch Height. First, we aimed to validate the use of the CSI in a group of participants with a variety of BMI scores (i.e., normal, overweight, and obese) by testing the relationship between CSI and navicular height. The partial correlation between CSI and navicular height controlling for BMI demonstrated a relationship between footprint and structural-based measurements for arch height ($r(18) = -0.56$, $P < 0.05$). Therefore, lower arches as indicated by a higher CSI were associated with lower navicular height measures in individuals with normal, overweight, and obese BMI scores. Next, we examined whether there were differences in CSI according to BMI classification. The one-way ANOVA with BMI classification as the independent variable and CSI as the dependent variable showed a significant difference in CSI for normal ($M = 0.21$; SD = 0.12), overweight ($M = 0.21$; SD = 0.14), and obese ($M = 0.32$; SD = 0.14) BMI groups: ($F(2,88) = 5.77$, $P < 0.01$). Higher values indicate lower arches. Follow-up pairwise comparisons showed that the obese group had lower arches than the normal and overweight groups (all Ps < 0.01, $d = -0.85$). Figure 3 shows CSI values for each participant by group.

3.3. BMI Classification, Arch Height, and Gait Parameters. Participants classified as overweight demonstrated a relationship between arch height and gait parameters. As illustrated in Figure 4, Pearson's correlations show that participants classified as overweight who had lower arches had slower velocities ($r(34) = -0.40$, $P < 0.05$), lower cadences ($r(34) = -0.39$, $P < 0.05$), and longer step times ($r(34) = 0.39$, $P < 0.05$), stance times ($r(34) = 0.49$, $P < 0.01$), and double limb support times ($r(34) = 0.54$, $P < 0.01$) than overweight participants with higher arches.

Results from the ANCOVA showed that CSI was related to velocity ($F(1,83) = 6.89$, $P < 0.05$, $d = 0.58$), double limb support time ($F(1,83) = 10.16$, $P < 0.01$, $d = 0.70$), stance time ($F(1,83) = 6.94$, $P < 0.05$, $d = 0.58$), step length ($F(1,83) = 4.40$, $P < 0.05$, $d = 0.45$), and foot rotation ($F(1,83) = 4.25$, $P < 0.05$, $d = 0.45$). Therefore, velocity, double limb support time, stance time, step length, and foot rotation were influenced by CSI. We also found significant interactions between CSI and BMI classification for velocity

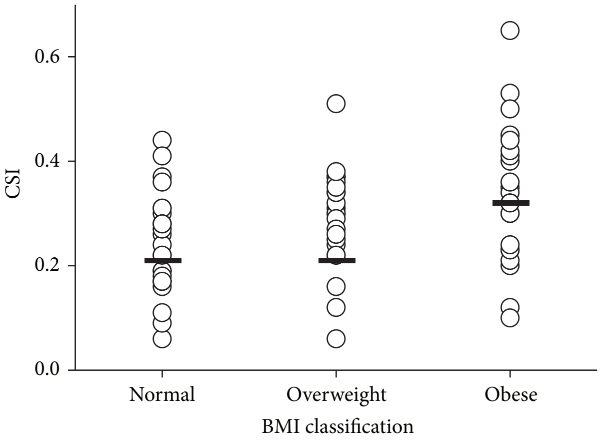

Figure 3: CSI values (y-axis) for each subject in every BMI classification group (x-axis). Horizontal bars represent group means. Note that when controlling for BMI, CSI and navicular height are significantly correlated ($r(18) = -0.56$, $P < 0.05$) indicating a relationship between footprint and structural-based measurements for arch height. Five categories are used to create qualitative descriptions of arch height based on CSI: elevated, normal, intermediate, lowered, and flat [27]. Those with overweight BMI scores represented arch heights that were elevated (8.3%), normal (62.5%), intermediate (20.9%), and lowered (8.3%). Those with overweight BMI scores had elevated (4.3%), normal (39.1%), intermediate (52.3%), and flat (4.3%) arches. Subjects with obese BMI scores exhibited normal (31.8%), intermediate (31.8%), lowered (18.2%), and flat (18.2%) arch heights.

($F(2,83) = 5.95$, $P < 0.05$, $d = 0.87$) and double limb support time ($F(2,83) = 12.97$, $P < 0.01$, $d = 1.28$). Follow-up analyses showed that participants classified as overweight with lower arches had slower velocities and longer double limb support times (all Ps < 0.01) than overweight participants with higher arches. But with the effect of CSI removed, BMI classification alone could not predict velocity, double limb support time, stance time, or step length (all Ps > 0.05). Although CSI did not predict step width, BMI classification predicted step width in the absence of CSI ($F(2,86) = 10.18$, $P < 0.001$, $d = 0.63$). We found no effects for cadence, single limb support time, step time, or swing time (all Ps > 0.05).

4. Discussion

The purpose of this study was to examine whether arch height would be a mediator of obesity-related characteristics in walking among adults with different BMI classifications. The findings showed that obese adults had lower arches than normal and overweight adults. Arch height predicted velocity, double limb support time, stance time, step length, and foot rotation. Overweight participants with lower arches had lower velocities and higher double limb support times than overweight participants with higher arches.

Our findings that arch height mediates walking parameters in the overweight population suggest that future investigations on the direct relationship between BMI classification and musculoskeletal injury should include an examination of both walking and arch height. These results are important because previous studies have mainly focused on other weight-related anthropometrics in relation to walking in this population.

This study was unique in its examination of the relationship between walking and arch height in adults with varied BMI classifications. In particular, our findings highlighted relationships between spatiotemporal walking parameters and arch height in overweight adults. Our results suggest that body mass and gait alterations that increase biomechanical stability during walking (e.g., increasing double limb support time) are associated with lower arches for overweight adults. The combination of gait modifications and lower arches in overweight adults could increase stability [15] and decrease the risk of falls and injuries [18]. It is plausible that lower arches (i.e., a wider footprint) in overweight adults may provide for better balance during walking. However, overweight adults may still require added stability with altered spatiotemporal kinematics by increasing the time that both feet are in contact with the ground (i.e., increasing double limb support time) and walking more slowly (i.e., decreasing velocity). This result also suggests that, for overweight adults, lower arches do not provide a stiff enough foot to exert a sufficient propulsive force that enables faster steps with limited foot contact on the ground [34]. In other words, although a lower arch via wider footprint may increase balance, a lower arch may be more flexible and less able to provide a forceful push off during walking.

Our results support a Goldilocks effect for how arch height mediated obesity-related spatiotemporal walking kinematics; perhaps normal BMI was too low and obese BMI was too high, but overweight BMI was just right for detecting arch height's effects on the BMI classification-kinematic relationship. This suggests that future testing with the overweight population may offer more insight into the mechanisms responsible for this relationship. In addition, there may be several reasons that we only found a relationship between walking and arch height for overweight participants. First, the relationship between arch height and walking based on spatiotemporal parameters may have highlighted this relationship in overweight participants and not obese or normal weight participants. Previous studies have found altered spatiotemporal gait parameters in obese adults [35], but these populations of obese adults had higher BMI scores than our current sample. Therefore, effects for obese adults with lower BMI scores may not be obvious with spatiotemporal parameters. Instead, obese adults in our study may have modified their gait in ways that could only be captured via advanced kinematic or kinetic methods. However, our results shed light on the fact that alterations in walking parameters were related to arch height in overweight but not normal or obese adults. For normal weight adults, arch height as it relates to spatiotemporal gait parameters could be less relevant because they may be better equipped to cope with variations in arch height; normal weight participants may have been able to alter their walking in multiple ways despite arch height. Second, footprint measures for obese adults may overestimate the number of adults classified as having "flat feet" due to increased adipose tissue [36].

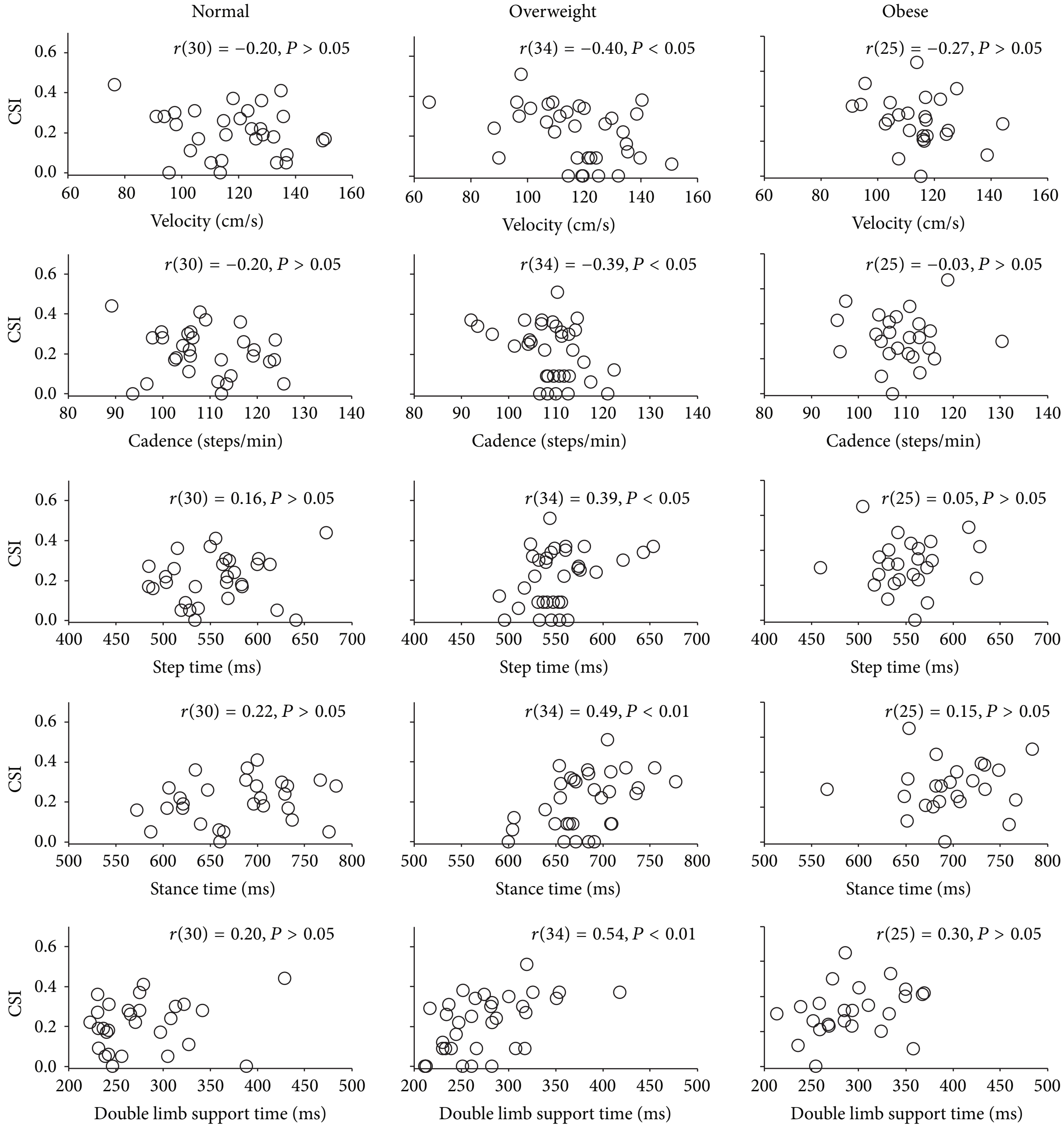

FIGURE 4: Pearson's correlations (r) between CSI (y-axis) and velocity, cadence, step time, stance time, and double limb support time (x-axes) for each BMI classification group. Each circle represents the average correlation for a participant.

We acknowledge finding modest relationships between arch height and spatiotemporal gait parameters for adults with overweight BMI scores. However, our results showing the relationship between footprint and structural measures for participants across all three BMI categories support our use of the digital footprint and subsequent CSI calculation for estimating the foot arch.

Our results have practical implications for aiding increased physical activity for overweight adults and for gaining a better understanding of how arch height may mediate walking based on BMI classification. In particular, these findings suggest that intervening in overweight adults' arch height may be important for supporting increased walking, a common and cost-effective method for increasing physical activity [3]. Adults who are overweight and who have lower arches may be more likely to respond to activity modification if provided with increased arch support. For example, orthotics designed to induce higher arches may facilitate an increase in walking by increasing velocity and decreasing double limb support times. Specifically, promoting an increase in physical activity for individuals who are overweight may prevent them from transitioning to becoming obese. The current findings are congruent with research suggesting that it is critical to address factors that contribute to walking difficulties in the overweight population in order to increase participation in physical activity [37]. Most importantly, these findings provide insight into how increased physical activity via walking can be supported in adults with overweight BMI scores.

One limitation for the current study includes using BMI to determine body composition and subsequent classification. We chose BMI to categorize our groups because it has been used for the same purposes in previous studies. Other methods of determining body composition and classification such as body fat percentage can yield more precise information about individuals' weight status. However, to ensure proper reliability, sophisticated equipment is usually required whereas BMI only requires height and weight measurements.

A second limitation includes that we did not capture nonweight bearing arch height in participants. This did not allow us to capture a measure of foot flexibility. However, the focus of the current study was on foot structure during a weight bearing activity.

A third limitation involves testing direct links between walking kinematics and arch height. With this being one of only a few studies to test the walking and arch height link in overweight and obese adults, we would expect questions to arise from the findings, which would lead to future studies. Future studies that make use of different methodologies (e.g., using both weight bearing and nonweight bearing measures of navicular height and measures of foot flexibility) are needed to investigate direct links between changes in gait mediated by arch height and musculoskeletal injury in overweight and obese individuals.

5. Conclusions

In conclusion, the findings suggest that arch height mediates obesity-related changes in spatiotemporal walking parameters. The data reported here are the first to find that kinematic changes associated with excessive weight may be contingent on foot anatomy and more specifically the height of the foot arch.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper and no relationship or conflict of interests with Clarks Corporation.

Authors' Contribution

Simone V. Gill, Cara L. Lewis, and Jeremy M. DeSilva participated in the design of the study. Simone V. Gill and Jeremy M. DeSilva conducted data collections. Simone V. Gill performed the statistical analyses. Simone V. Gill, Cara L. Lewis, and Jeremy M. DeSilva helped to draft and edit the paper. All authors read and approved the final paper.

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