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A reduction in the knee adduction moment with medial thrust gait is associated with a medial shift in center of plantar pressure

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ABSTRACT

The knee adduction moment (KAM) is an established marker of compartmental load distribution across the tibiofemoral joint. Research suggests a link between the magnitude of the KAM and center of plantar pressure (COP) thus alterations in the two may be related. The objective of this study was to investigate whether the COP predictably shifts when the KAM is reduced through a gait adaptation. Twenty healthy adults underwent gait analysis walking with their normal gait pattern and with medial thrust gait, a gait adaptation known to significantly reduce the KAM. Simultaneous COP and 3-D kinetics were acquired to allow for a comparison of the change in COP to the change in the KAM. The COP was quantified by determining a customized medial-lateral pressure index (MLPI) which compares the COP tracing line during the first and second halves of stance to the longitudinal axis of the foot. Linear regressions assessing the association between the changes in KAM and MLPI indicated that 48.3% ($p = 0.001$) of the variation in MLPI during the first half of stance can be explained by the KAM during the same period. A trend was observed between the association between the KAM and MLPI during the second half of stance ($R^2 = 0.16$, $p = 0.080$). Backwards elimination regression analysis was used to explore whether simultaneous consideration of the KAM and other potential confounding factors such as sagittal plane knee moments and speed explained variance in the MLPI during the first half of stance. Only the KAM exhibited explanatory power ($\beta = 0.695$, $p = 0.001$). During medial thrust gait, a reduction in the KAM was associated with a medial shift in the MLPI, and an increase in the KAM was associated with a lateral shift in the MLPI, especially in the first half of the stance phase. Together, these results demonstrate an inherent link between foot pressure and the KAM during medial thrust gait, and suggest that manipulating foot pressure may be a biomechanical mechanism for an intervention designed to improve loading conditions at the knee.

1. Introduction

Load distribution across the tibiofemoral joint is asymmetric and highly predicted by the knee adduction moment (KAM), an external kinetic marker obtained during motion analysis [1,2]. The KAM has repeatedly been utilized as a surrogate marker of load distribution across the tibiofemoral joint [3,4]. A higher than normal peak KAM suggests higher than normal knee loading during gait and is characteristic of gait in individuals with knee osteoarthritis (OA) [5], those with varus aligned, anterior cruciate ligament deficient knees [6], and patients who have undergone meniscectomy [7,8], making this a variable of significant interest in gait analysis.

The center of foot pressure (COP) is the point of origin of the ground reaction force. Shifts in the COP inherently affect the ground reaction force and likely impact loading at the knee. While the literature suggests a relationship between the KAM and COP in studies examining the effects of specialized footwear [9–19], it is currently unclear how shifts in the COP are related to changes in the KAM, particularly with a gait modification designed to lower

Abbreviations: COP, center of pressure; KAM, knee adduction moment; KAM1, first peak knee adduction moment; KAM2, second peak knee adduction moment; MLPI, medial-lateral pressure index; MLPI1, medial-lateral pressure index during the first half of stance; MLPI 2, medial-lateral pressure index during the second half of stance; OA, osteoarthritis.

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the KAM. The COP is lateralized in those with medial knee OA compared with healthy subjects [20] suggesting that a medialization of COP may reduce the KAM. However, debate exists in the literature, with reports of a medial shift in COP [10,15,19] a lateral shift in COP [11,13,14,21,22], or no shift [23] occurring with reductions in the KAM. An improved understanding of an association between plantar pressure and knee loads would suggest an indirect but efficacious avenue to target knee loads, which is historically difficult to accomplish long term. Thus, an investigation of how COP and KAM change concurrently during a gait modification known to affect the KAM is warranted and could lead to future development of biomechanically-based interventions directed at manipulating foot pressure to lower excess loads at the knee.

Changes in COP have been characterized and quantified during walking both with shoes and while barefoot. The most frequently utilized methodology estimates rather than directly measuring the COP between the shoe and floor using the origin of the ground reaction force on a force plate [9,13–15,19,22–26]. This method has drawbacks, particularly since the COP is often compared to an unstable point(s) of reference (reflective markers) which may alter the overall findings. Also, the properties of the shoe can affect or obfuscate the actual pressure between the shoe and the force plate, resulting in an inaccurate assessment of pressure [27]. Measuring COP during barefoot walking arguably imparts the least amount of confounding variables and has been quantified using a pressure plate in a few studies [20,28,29]. A pressure plate is more sensitive at detecting variability between subjects [27]. It has been suggested that this is either because of the shoe constraints on the foot-insole interface, or because of inter-subject variability of foot mobility during barefoot walking [27]. To our knowledge no study has quantified a shift in barefoot COP as it relates to the KAM.

The objective of this study was to investigate the relationship between changes in the KAM and the resultant changes in COP when walking with medial thrust gait. In the present work, we investigate whether the COP predictably shifts when the KAM is changed in a population of healthy adults walking with a medial thrust gait modification designed to reduce the KAM. Medial thrust gait likely reduces the moment arm of the ground reaction force to lower the KAM by adjusting the lower leg positioning [30]. Similarly, biomechanical interventions applied to the foot likely act by altering lower limb kinematics, which translate to a decrease in the moment arm at the knee. Our primary hypothesis is that a reduction in the KAM during medial thrust gait will be associated with a medial shift in COP both during the first and second halves of the stance phase of gait.

2. Methods

This single day cross-sectional study tested healthy subjects walking barefoot with their normal gait and subsequently with a medial thrust gait alteration to elicit a change in their KAM. Healthy subjects were chosen in order to examine individuals with relatively normal foot structure and function who were free of pain and joint disease. While those with or at-risk for joint disease are ultimately the target population for gait modifications that alter plantar pressure and the KAM, we believe that first examining this relationship in healthy subjects provides the best picture of this inherent relationship.

Following approval from Rush University's Institutional Review Board, subject recruitment was performed by word of mouth within the university. Informed consent was obtained, and subjects who both self-reported as healthy and pain free (<10 mm on a 100 mm visual analog scale) in their lower limb joints and who were without a recent history of knee pathology or recent lower extremity injury were enrolled in the study.

Subjects walked barefoot at a self-selected normal speed with their normal gait pattern across a leveled six-meter walkway containing a pressure platform stacked onto a force plate. After completing five normal walking trials, subjects were trained to walk with a medial thrust gait alteration and then completed five walking trials with the medial thrust gait pattern. Medial thrust gait was chosen for the study protocol because it has been shown to result in significant reductions in the KAM [26,31–33], specifically during early stance [34]. It was also chosen because it has direct effects on the moment arm of the ground reaction force by moving the knee joint center closer to the GRF vector, which is the likely mechanism whereby biomechanical interventions applied to the foot elicit reductions in the KAM.

Gait assessment was performed using a 24-marker, modified Helen Hayes marker set. The model combined the Helen Hayes [35] model with our existing 6-marker link model [36], increasing the functionality of the model by viewing segments as 3-D planes instead of 2-D lines. Thigh and shank markers were moved off the long axis of the segment to create a segment plane. Hip joint center and sagittal plane hip motion were defined using the link model. The hip joint center was defined as 2.5 cm distal to the midpoint of a line from the anterior-superior iliac spine to the pubic tubercle [37]. Medial markers at knee and ankle, used only during a static collection, defined respective joint centers. The knee joint center was defined as the midpoint between the lateral and medial knee joint line markers. The ankle joint center was defined as the midpoint between the markers on the lateral and medial malleoli.

Motion capture was performed using twelve optoelectric cameras (Qualysis, Gothenburg, Sweden) to capture lower extremity kinematics. Ground reaction forces were measured with a ground embedded force plate (Bertec, Columbus, OH, USA). Raw kinetic and kinematic data were processed in The Motion Monitor software (Innovative Sports Training, Chicago, IL, USA). Simultaneous COP and 3D ground reaction forces were acquired by mounting a 3 mm high tile onto the ground embedded force plate and mounting a pressure platform (emed, Novel, Munich, Germany) onto the tile. The tile kept the emed platform clear of the stationary flooring adjacent to the embedded force plate. The stacked assembly was leveled with the walkway. All three capture systems were run at a frequency of 100 Hz to allow for accurate syncing of the desired stance phase variables. Bilateral kinematic data were obtained; however, the left side was randomly predetermined to serve as the indexed limb. Thus, only left sided plantar pressure and force data were analyzed and reported in this study. Kinematic and ground reaction force data were smoothed with a fourth order Butterworth filter at 15 Hz in MATLAB 2013b (The MathWorks, Inc., Natick, Massachusetts, United States). Knee moments were calculated with inverse dynamics using previously published methods [35] and normalized for body weight and height [38].

Subjects performed all walking trials using a 3-step method where force data is collected during the third step. The 3-step method was chosen over a 1-step or 2-step method to increase the likelihood of achieving a steady state gait pattern [39,40]. No attention was drawn to the pressure plate. Since KAM during stance is bimodal, the stance phase was bisected; the first and second halves of stance were analyzed separately for both the KAM and COP. The kinetic and COP data during the first and second halves of stance for five successful normal walking trials were averaged for each subject. The first peak KAM (KAM1) and second peak KAM (KAM2) were defined as the maximum adduction moment during the first 50% of stance and second 50% of stance, respectively.

After completing the five normal barefoot walking trials, subjects were trained by the same experienced physical therapist (CF) to walk with a medial thrust gait modification [26] according to previously published methods [26,30,31,41]. Subjects were