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Sex-specific kinetic and kinematic indicators of medial tibiofemoral force during walking and running

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ABSTRACT

Background: Our aims were to (1) Evaluate sex-specific contributions of peak knee flexion moment (pKFM) and peak knee adduction moment (pKAM) in medial tibiofemoral joint (TFJ) force during walking and running; (2) identify kinematic variables to estimate peak medial TFJ force.
Methods: Eighty-seven runners participated (36 females, 51 males; age = 23.0 ± 3.8 years (1 standard deviation)). Kinematics and kinetics data were collected during treadmill walking (1.3 m/s) and running (3.0 ± 0.4 m/s). Peak medial TFJ contact force was estimated using a musculoskeletal model. Linear regression analyses were used to assess the contribution of pKFM, pKAM and kinematic indicators to estimated joint forces.
Results: During walking and running, pKAM and pKFM accounted for 74.9% and 64.5% of peak medial TFJ force variance ($P < 0.001$), respectively. Similar pKAM contribution was found between males and females during walking (51.8% vs. 47.9%), as opposed to running (50.4% vs. 26.8%). Kinematic indicators during walking were peak knee flexion and adduction angles, regardless of sex. During running, indicators were ankle dorsiflexion at foot strike and center of mass (COM) vertical displacement in females ($R^2 = 0.364$, $P = 0.012$), and peak knee abduction angle and step length in males ($R^2 = 0.508$, $P = 0.019$).
Conclusion: We conclude from these results that pKAM and pKFM make significant but potentially sex-specific contributions to peak medial TFJ force during walking and running. Clinically, peak medial TFJ force during walking can be estimated using peak knee flexion and adduction angles in both sexes. During running, ankle dorsiflexion at foot strike and COM oscillation are best indicators among females, while knee abduction and step length are best among males.

1. Introduction

The knee joint is subject to considerable compressive forces during human locomotion. It has been suggested that the tibiofemoral joint (TFJ) sustains forces of approximately 2.8 bodyweights during the stance phase of walking, while as much as

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eight to 12 bodyweights are applied during running [1,2]. In either activity, the medial compartment experiences greater loads than its lateral counterpart [1]. Considering the higher prevalence of traumatic injuries [3] and degenerative changes [4] to the medial compartment compared with the lateral compartment, a better understanding of contributions to medial TFJ contact force in both the research and clinical settings may better inform injury prevention efforts and foster development of gait modifications to aid in treatment of medial compartment conditions.

Laboratory-based musculoskeletal models can be used to estimate medial TFJ contact force during walking and running [5,6]. However, the peak knee adduction moment (pKAM) is a widely utilized surrogate for medial TFJ force, and is highly correlated with medial compartment peak force during a variety of walking tasks [7,8]. Sagittal plane knee joint moments may also contribute substantially to medial TFJ force during walking [9,10]. Manal, reported pKAM and peak knee flexion moment (pKFM) together explained 85% of peak medial TFJ force variance [9]. Based on previous literature, however, it remains unknown if sex-specific contributions of pKAM and pKFM influence medial TFJ force during walking. In addition, only one study [1] to date has investigated the relative contribution of pKAM and pKFM to medial TFJ force during running. Saxby et al. reported that combining pKFM and ground reaction forces explained 45% of variance in medial TFJ force during running. Interestingly, pKAM was not included in their final regression model for running, even though it was found to be important in estimating medial TFJ force during walking [1]. It must be noted that, despite the inclusion of a mixed sex cohort, potential sex differences were not examined. Anatomical and biomechanical differences between males and females likely result in unique contributions to medial compartment loads and warrant further analysis [11–13]. Importantly, sex-specific analyses of gait mechanics relevant to medial TFJ force appear justified to inform optimal sex-specific interventions.

To effectively translate laboratory findings to a clinical environment, it is prudent to identify clinically measureable indicators of medial TFJ contact forces during walking and running. Ideally, these gait metrics could be modifiable and measured using technology commonplace in clinical environments, so that treatment options can be suggested to individuals with knee disorders. Measurement of gait kinematics is feasible in a clinical environment using simple two-dimensional (2D) video and may provide useful information regarding joint kinetics [14,15]. For example during walking, foot adduction (toeing-in) and increased step width decreased pKAM during a single testing session [16–19]; foot adduction also contributed to significant improvements in symptoms and function in individuals with medial tibiofemoral compartment osteoarthritis (OA) [20]. During running, Willy et al. reported that increasing step rate (effectively reducing step length) reduced medial TFJ force [6]. Based on such results, it is possible that these and other clinically measurable kinematic variables previously reported as being altered by step rate manipulations such as step length [21], ankle angle at footstrike [22] and vertical displacement of the center of mass (COM) [23] also contribute to medial TFJ force during running. To date, however, the relative contribution of these feasible clinical gait measurements to medial TFJ force during walking and running has not been explored.

Knowledge of sex-specific contributions of sagittal and frontal plane knee moments to peak medial TFJ force during walking and running may inform future intervention studies in different patient populations. In addition, clinically applicable indicators of medial TFJ force are necessary to provide a basis for eventual clinical interventions. The objectives of this study were to (1) evaluate the sex-specific contribution of pKFM and pKAM in medial TFJ forces during walking and running; (2) identify kinematic variables obtainable within a clinical setting to estimate peak medial TFJ loads during walking and running. We hypothesized that (1) pKFM and pKAM would account for different proportions of medial TFJ force in males and females, and that (2) a set of sex-specific walking and running kinematic measurements could provide accurate estimations of medial TFJ force.

2. Methods

2.1. Participants

The study was approved by the East Carolina University Institutional Human Subjects Research Board, and all participants gave their written and verbal consent before enrolling in the study. A total of 87 subjects (36 females and 51 males) were recruited from written advertisements posted on University campus (Table 1). To be eligible, participants had to be healthy individuals, aged between 18 and 35 years and injury-free at the moment of data collection and during the previous three months. In addition, participants were required to run ≥10 km per week for at least the previous three months and score ≥8/10 on a visual analog scale assessing treadmill during walking and running (0 = completely uncomfortable; 10 = completely comfortable) [24].

2.2. Assessment of walking and running mechanics

A device-mounted digital inclinometer was used to evaluate tibial mechanical axis. In the standing position, the device was aligned with the center of the talus and the tibial tuberosity [25]. Next, participants were prepared for the walking and running trials according to previously reported methods [26]. Retroreflective markers to create segment coordinate systems were temporarily applied bilaterally at the anterior tip of the shoe, head of first and fifth metatarsals, medial and lateral malleoli, medial and lateral proximal tibia, medial and lateral femoral condyles, greater trochanter, anterior superior iliac spine, iliac crest, and acromiohumeral space. Rigid clusters of tracking markers were securely mounted to the posterior aspect of the shank and thigh bilaterally, as well as to the pelvis. A cluster of three markers was mounted on the heel counter of each shoe (Saucony ProGrid Ride, Saucony, IN, USA) and four markers in the thoracic spine region.

A 10-camera motion analysis system (Qualisys Corporation, Gothenburg, Sweden) was used to collect kinematics data at 200 Hz, which were synchronized with ground reaction force data sampled at 1000 Hz. First, static calibration and functional

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