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Normalization influences knee abduction moment results: Could it influence ACL-injury research, too?

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ABSTRACT

Objectives: Normalization of joint moments to reduce anthropometric influences prior to making group comparisons is a widely-accepted practice. However, a seminal prospective study reported greater non-normalized knee abduction moment (KAM) in nine females who subsequently sustained an ACL injury. It is not clear if this finding may have been influenced by the fact that the ACL-injured females were on average 3.6 cm taller and 2.4 kg heavier than uninjured females.
Design: Cross-sectional.
Methods: Peak KAM was identified in thirty-six females completing jump landings. A custom software program randomly divided participants into two groups that were compared on: (1) non-normalized KAM, (2) KAM normalized to body mass, and (3) KAM normalized to body height times weight a total of 500,000 times and the results categorically coded for statistical significance ($\alpha \leq 0.05$). For the 10,591 iterations in which one group was 3–4 cm taller and 2–3 kg heavier, the agreement between results obtained using non-normalized *versus* normalized data were assessed using non-parametric analyses.
Results: Despite moderate-strong agreement between the results obtained using non-normalized and normalized data ($K = 0.614$–0.744), a significant effect of normalization on the interpretation of group differences in peak KAM was identified ($p < 0.001$). In 30.4–41.9% of the cases in which non-normalized KAM was deemed significantly different between groups, no group differences were identified when using normalized KAM.
Conclusions: While it is unlikely the magnitude of the difference in non-normalized KAM identified prospectively in ACL-injured females was attributable solely to anthropometric differences, caution should be exercised when evaluating research findings reporting non-normalized KAM.

1. Introduction

Over the past several decades, a key focus area in anterior cruciate ligament (ACL) injury risk-related research has been on excessive external knee abduction moments (KAM) during various movement tasks. While *in vitro* work by Markolf et al.[1] linked frontal plane knee moments and ACL loading more than twenty years ago; the foundation for much of the continued interest in KAM among the scientific community is the seminal prospective study by Hewett et al.[2] in which peak KAM during a drop vertical jump was significantly greater in 9 female athletes who went on to sustain a non-contact ACL injury event compared to 205 uninjured females. This investigation has been cited over 825 times as of July 2016,[3] served as the foundation for many subsequent investigations evaluating KAM over numerous types of movement tasks,[4–7] and is prominent in several well-known review articles describing mechanisms of ACL injury.[8–10] However, one concern that continues to persist despite the significant influence of this investigation is that the authors did not normalize the KAM of study participants prior to statistical analysis.

Commonly, between subject variation in joint moments due to differences in height and mass is reduced through normalization, so that any significant differences that are identified when making comparisons between groups can be attributed to differences in movement mechanics and not anthropometrics.[11,12] Numerous normalization methods exist with two of the most common

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being to divide the joint moment by either (1) body mass or (2) the product of body weight and height.[11] Despite this, Hewett et al.[2] did not normalize KAM prior to comparing groups, perhaps due to the fact that "[t]he ACL-injured population was similar in. . .height (167.7 ± 6.8 cm *vs* 164.1 ± 6.0 cm; *P* = 0.08), and weight (61.5 ± 8.3 kg *vs* 59.1 ± 8.1 kg; *P* = 0.39) to uninjured controls".[2] However, given that the purpose of normalization is to eliminate the influence of individual rather than group differences in anthropometrics, it is not clear to what extent, if any, the greater KAM of the ACL-injured females in this study may have been due to the fact that on average they were 3.6 cm taller and 2.4 kg heavier than their uninjured counterparts. Therefore, the purpose of this investigation was to examine the agreement in comparisons of peak KAM made using non-normalized *versus* normalized data between groups exhibiting small, but not statistically significant, differences in height and mass.

2. Methods

Thirty-six, healthy, recreationally active female volunteers between 18–30 years old (age = 21.0 ± 1.7 years; height = 168.0 cm ± 7.9 cm; mass 65.6 kg ± 8.7 kg) participated in this investigation. Recreationally active was defined as participating in at least 150 min of moderate to vigorous physical activity per week.[13] All participants reported: (1) no history of lower extremity surgery; (2) no current injury or illness which limited their physical activity level; (3) no leg or low back injury in the last 6 months which limited their physical activity; (4) no previous ACL injury, and (5) that they had participated in an activity involving cutting or jumping within the last 6 months. In addition, they were asked not to partake in any strenuous exercise 24 h prior to the testing session. Upon arrival at the testing site, all participants were informed of the study procedures and risks of participation, and provided written consent. The study protocol was approved by the Institutional Review Board at Oregon State University.

Following study enrollment, participants completed a 5 min warm-up at a moderate intensity on a stationary bike. They were outfitted in spandex shorts and tank top and wore their own athletic shoes during testing. The height and mass of each participant was recorded prior to data collection for biomechanical model generation and normalization of the dependent variables. Participants were outfitted with a retro-reflective marker set (27 static, 23 dynamic) placed bilaterally on the acromion process, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, anterior thigh, medial and lateral femoral epicondyles, anterior shank, and medial and lateral malleoli as well as over S1. Markers were also placed bilaterally on the shoes over the approximate locations of the calcaneus and the 1st and 5th metatarsal heads. Nine motion capture cameras (Vicon, Inc., Centennial, CO, USA) were used to record marker positions during one static subject calibration trial and three double-leg jump landing trials that were performed after removing the medial femoral epicondyle and medial malleoli markers. Jump landing trials in which participants jumped down and forward from a 30 cm high box placed 50% of their height behind two force plates (Bertec Corporation, Columbus, OH, USA), landed with both feet at the same time, and then jumped vertically for maximum height in a fluid motion were analyzed.[14,15]

Kinematic and force plate data were sampled at 120 and 1560 Hz, respectively, using Vicon motion capture software. Raw three-dimensional kinematic coordinates and force plate data were imported into The MotionMonitor motion analysis software (Innovative Sports Training, Chicago, IL, USA) and a biomechanical model was generated using previously described methods.[16] Kinematic data were low-pass filtered at 9 Hz using a 4th order zero-phase lag Butterworth digital filter, time-synchronized to force plate data, and re-sampled at 1560 Hz. Force plate data were digitally low-pass filtered using a 4th order zero-phase lag Butterworth filter at a cutoff frequency of 50 Hz. Despite the influence that filtering kinematic and kinetic data at different frequencies can have,[17,18] these cut-off frequencies were specifically chosen to replicate those used by Hewett et al.[2] Frontal plane inter-segmental knee moment of force was calculated using an inverse dynamics solution within The MotionMonitor using the methods described by Gagnon and Gagnon[19] with the result expressed as an external moment. Custom computer software (LabVIEW Inc., National Instruments, Austin, TX, USA) was used to identify peak KAM during the landing phase of each trial for the right limb of all participants. The landing phase was operationally defined as the time from initial ground contact to the first local minimum of the vertical ground-reaction force.[2,20] Peak KAM values were averaged across the three jump-landing trials and normalized to produce three distinct KAM outcome variables: (1) non-normalized KAM, (2) KAM normalized to body mass, and (3) KAM normalized to the product of body weight and height.

A second custom computer software program (LabVIEW Inc.) was used to evaluate the potential influence of normalization on the interpretation of group differences in peak KAM. The software program used a random number generator to divide the 36 participants into two groups of 18 with this procedure repeated a total of 500,000 times, which represents about 1% of the approximately 4.5 billion possible independent group combinations. For each of these 500,000 iterations, the randomly created groups were compared for differences in height, mass, non-normalized KAM, KAM normalized to body mass, and KAM normalized to the product of body weight and height using five separate one-way ANOVA models. The ANOVA results were written to a spreadsheet and then coded as either statistically significant (Yes) when $p \leq 0.05$ or not statistically significant (No) when $p > 0.05$. Finally, iterations that resulted in one group being 3–4 cm taller and 2–3 kg heavier than the other group, but not significantly different on either measure ($p > 0.05$), were identified. These ranges were chosen to mirror the magnitude of the differences in average height (3.6 cm) and mass (2.4 kg) between ACL-injured and uninjured females in the study of Hewett et al.[2] There were 10,591 iterations that met these inclusion criteria that were extracted for statistical analysis.

The agreement between the results obtained using non-normalized and the two normalized peak KAM measures were then assessed separately in two ways. *Absolute* agreement, or agreement between the results obtained using non-normalized and normalized data when considering all cells in the 2 × 2 table, was assessed using Cohen's kappa coefficients. McNemar's tests, which only include data from cells of the 2 × 2 table that indicate disagreement between methods, were used to assess *relative* agreement by testing marginal homogeneity, or the equality between the row and corresponding column proportions. All analyses were conducted using IBM SPSS Statistics 23.0 (IBM, Armonk, NY, USA).

3. Results

There was a moderate-strong agreement between the interpretation of group differences in peak KAM when using non-normalized KAM and the interpretation when KAM was normalized to body mass ($K = 0.744$, $p < 0.001$) or the product of body weight and height ($K = 0.614$, $p < 0.001$). However, the results of the McNemar's tests identified a significant effect of normalization on the interpretation of group differences in peak KAM for both the body mass ($X^2 = 31.8$, $p < 0.001$) and product of body weight and height ($X^2 = 21.5$, $p < 0.001$) normalization methods as evidenced by inequality between the row and corresponding column proportions (Table 1).

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