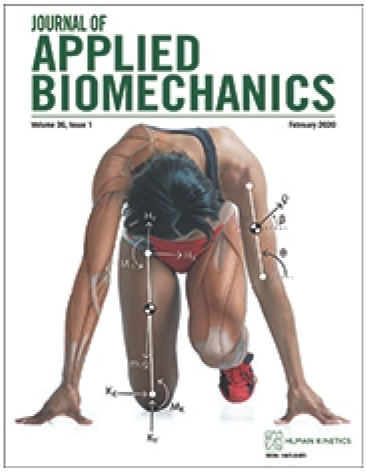

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Increasing breast support is associated with a distal-to-proximal redistribution of joint negative work during a double-limb landing task

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Abstract

Female athletes exhibit greater rates of ACL injury compared to male athletes. Biomechanical factors are suggested to contribute to sex-differences in injury rates. No previous investigation has evaluated the role of breast support on landing biomechanics. This study investigates the effect of breast support on joint negative work and joint contributions to total negative work during landing. Thirty-five female athletes performed five landing trials in three breast support conditions. Lower extremity joint negative work and relative joint contributions to total negative work were calculated. Univariate ANOVAs were used to determine the effect of breast support on negative joint work values. Increasing levels of breast support were associated with lower ankle negative work ($p < 0.001$) and ankle relative contributions ($p < 0.001$) and increases in hip negative work ($p = 0.008$) and hip relative contributions ($p < 0.001$). No changes were observed in total negative work ($p = 0.759$), knee negative work ($p = 0.059$) or knee contributions to negative work ($p = 0.094$). This data demonstrates that the level of breast support affects lower extremity biomechanics. The distal-to-proximal shift in negative joint work and relative joint contributions may be indicative of a more protective landing strategy for ACL injuries.

Keywords: biomechanics, breast, sports bra, ACL, injury

Word Count: 3244

Introduction

Sport participation has seen a large increase in the number of female athletes over the past 45 years[1]. Greater female sport participation has resulted in a concomitant increase in the number of musculoskeletal injuries. However, the rate of musculoskeletal injuries in female athletes has outpaced the increasing rate of female sport participation resulting in a disparity in the rate of traumatic knee injuries in female compared to male athletes. For example, female athletes experience ACL ruptures at a 2.5- to 6.2-fold greater rate than their male counterparts in sex-comparable sports [1,2]. The observed sex differences in injury rate emerge with sexual maturation.

Sex-based differences in anatomical morphology [3,4] and hormonal profiles [5,6] have been suggested to contribute to an increased risk of ACL injury in female compared to male athletes. Breast development is a sex-specific trait that emerges during maturation [7] that has been shown to alter movement biomechanics. Mechanically, the breast has been described as a “wobbling mass” situated on a rigid torso that moves in conjunction with the torso and upper extremities in the natural condition [8]. Moreover, breast motion occurs with a significant time lag compared to torso motion evidenced by a delay in onset of movement of the passive breast tissue relative to the trunk [9]. It is suggested that this breast-body time lag presents a perturbation to trunk control during sports-based movements. These perturbations are purported to have secondary influences on both upper and lower extremity kinematics [8,10-12]. In treadmill running, greater breast support (low support, and high support sports bra) has been shown to reduce breast lag resulting in altered trunk, pelvis and upper extremity kinematics[8]. The alterations of trunk, pelvis, and upper extremity kinematics with high breast support has been shown to increase energy preservation and is beneficial to running performance for female athletes during running[8]. Data reported by

Fong & Powell [13] further support the notion that increasing breast support improves running performance by demonstrating that greater breast support is associated with reduced oxygen consumption and greater running economy during treadmill running. Mechanically, during over running, increased breast support has been associated with greater stride lengths, reduced cadence, greater vertical trunk displacements [10] and greater knee joint stiffness [11]. These findings demonstrate that breast support not only affects breast motion but has secondary effects lower extremity biomechanics and running performance [8,10,11,13].

Sex-based differences in lower extremity biomechanics patterns have been reported during sport-relevant movements such as jumping, landing and cutting [14-18]. Evidence has demonstrated that female athletes utilize unique landing biomechanics compared to male athletes [12,14,16]. Moreover, sex-based differences in anthropometry have been implicated in these distinct movement patterns as well as greater injury rates in female compared to male athletes [19-23]. In landing, female athletes exhibit greater vertical ground reaction forces (GRF) magnitudes, greater peak dorsiflexion angles and smaller peak knee flexion angles compared to male athletes [16,24,25]. Female athletes also exhibit greater initial plantarflexion, greater ankle joint ranges of motion, greater ankle joint velocities and greater energy absorption than male athletes [14,26]. At the knee, female athletes exhibit a quadriceps dominant landing pattern characterized by greater knee extensor moments, and greater knee-to-hip extensor moment ratios [14,18,26,27]. Further, female athletes absorb less energy at the hip as evidenced by smaller relative hip joint contributions to landing [14]. Though solely focused on the sagittal plane, research findings demonstrate that female athletes implement a distinct multi-joint biomechanical strategy than male athletes during landing tasks. The adoption of a preferred hip dominant strategy in collegiate female athletes, more closely mimicking landing patterns of male athletes, has been shown to result in less injurious movement patterns [28]. Commonly, researchers have used joint work and relative joint contributions to lower extremity work to quantify landing strategy as it relates to lower extremity injury including rupture of the anterior cruciate ligament [29,30].

Sex-based differences in biomechanics contribute to greater rates of ACL injury in female compared to male athletes. Though a small number of studies have investigated the role of sports bra support on breast motion during jumping and landing movements [31,32], only a single study has directly investigated the secondary effects of sports bra support on lower extremity biomechanics during a landing task. During landing, increasing breast support has been associated with reductions in peak knee flexion angles, knee valgus angles, and knee valgus moments, as well as increases in trunk flexion angles at initial contact and peak trunk flexion angles [33]. This suggests that lower levels of breast support are associated with knee joint and trunk profiles suggestive of an increase in ACL injury risk. Therefore, the purpose of this study was to determine the effect of breast support on lower extremity joint negative work and relative contributions to lower extremity negative work during a landing task. It was postulated that increasing the level of breast support would reduce constraints on the neuromuscular system associated with breast motion relative to the trunk and would result in landing biomechanics more closely associated with that of male athletes characterized by greater reliance upon proximal compared to distal musculature. It was hypothesized that increasing breast support would be associated with reductions in ankle joint negative work and increases in hip joint negative work during the landing task. It was further hypothesized that relative ankle joint contributions to landing work would be reduced and relative hip joint contributions to landing work would be increased in response to increasing breast support.

Methods

Participants: A power analysis was conducted using preliminary lower extremity joint work data. An effect size calculation was based on the differences in ankle and hip joint work (averaged) during a landing task from a single preliminary participant in the low compared to high support sports bra conditions. In G-Power, using an effect size of 0.5, a power value ($1 - \beta$) of 0.80 and an α of 0.05, determined a necessary sample size of 34 participants to be an appropriate sample size to detect support-related differences in lower extremity joint kinetics during a landing task. Therefore, thirty-five female recreational athletes were recruited to participate in this study (Table 1). To be included in the study, athletes had to (1) be aged 18 to 35 years, (2) have a self-reported bra size of B-, C- or D-Cup and (3) have no history of breast augmentation surgeries (reductions or implants) and (4) participate in a multi-directional sport (i.e. basketball, soccer, etc.). All participants were free from a recent history (6 months) of musculoskeletal injury that would negatively affect the participant's ability to perform a landing task. The experimental protocol was approved by the University Institutional Review Board and all participants provided written informed consent prior to study participation.

Instrumentation: GRFs and three-dimensional kinematics were recorded simultaneously using an 8-camera motion capture system (240 Hz, Qualisys AB, Goteburg, Sweden) and two force platforms (1200 Hz, AMTI Inc., Watertown, MA, USA) embedded in the laboratory floor. Participants performed landing trials in spandex shorts and sports bras (based on condition) to limit marker occlusion during dynamic testing. Participants completed testing in their personal footwear. A kinematic model was built using 14 mm retroreflective markers and included the pelvis as well bilateral thigh, shank and foot segments. Anatomical markers were placed over the bilateral anterior superior iliac spines, posterior superior iliac spines, iliac crest and trochanters.

Anatomical markers were also placed over the medial and lateral femoral epicondyles, medial and lateral malleoli, and the first and fifth metatarsal heads. The pelvis, thigh and shank were tracked using rigid clusters of four retroreflective markers while the rearfoot was tracked using three individual retroreflective markers placed over the superior, inferior and lateral calcaneus. To track breast motion, individual retroreflective markers were placed over the superior sternum as well as right and left nipples [34]. After a standing calibration, all anatomical markers were removed leaving only tracking markers for the breasts, pelvis, thigh, shank and rearfoot.

Experimental Protocol: Prior to data collection, participant anthropometrics were recorded including age (yrs), height (m), mass (kg), over-bust chest circumference (cm) and under-bust chest circumference (rib cage; cm) at the level of the infra-mammary fold [35]. Bust and ribcage circumferences were measured as previously described [36]. Each participant was then professionally fitted into two different sports bras, one marketed to provide a high level of breast support (Ultimate, SheFit Inc., Hudsonville, MI, USA) and one marketed to provide a low level of breast support (Flex, SheFit Inc., Hudsonville, MI, USA). Sports bra fitting was conducted as described by the manufacturer.

Prior to data collection, participants completed a 10-minute warm up which included light aerobic activity (treadmill running or stationary cycling) and light stretching. Each participant then performed five successful step-off landing trials from a 0.40 m box in three different breast support conditions in a randomized order: control (CON; no support, i.e. bare-breasted), low support (LOW; SheFit Flex low support sports bra) and high support (HIGH; SheFit Ultimate high support sports bra). A successful landing trial was characterized by the participant performing a double-limb landing with each foot on an independent force platform and maintaining a stable landing posture. Participants were allowed to practice the landing task prior to data collection until they were comfortable with the task and consistently maintained a stable posture upon landing.

Data Analysis: Landing data were analyzed from initial contact (IC) to peak knee flexion. This period represents the eccentric phase [37] of the landing task. IC was determined as the instant at which the vertical GRF exceeded a threshold of 20 N for a period greater than 0.10 s. Visual3D (C-Motion Inc., Bethesda, MD, USA) was used to filter kinematic and GRF data, and to calculate ankle, knee and hip joint powers. Retroreflective marker trajectories and GRF data were filtered using a fourth-order, zero-lag Butterworth lowpass filter with cutoff frequencies of 12 Hz and 50 Hz, respectively[38,39]. Custom software (MATLAB, MathWorks, Natick, MA, USA) was used to calculate negative joint work at the ankle, knee and hip. Vertical breast position was calculated as the difference in vertical position between the superior sternum marker and right and left nipple markers, respectively. Vertical breast displacement was then calculated as the difference in vertical breast position (relative to the sternum) at contact compared to minimum vertical breast position. Negative joint work values were calculated as the negative values of the joint power time-series integrated with respect to time. Relative joint negative work was calculated as the quotient of an individual joint negative work divided by total lower extremity joint negative work. Total lower extremity joint negative work was defined as the sum of ankle, knee and hip joint negative work. Participant means for absolute and relative joint negative work were calculated as the average of the five trials in each condition. Participant means were included in the statistical analyses.

Statistical Analysis: A 1 x 3 univariate repeated measures analysis of variance (ANOVA) was used to determine the effect of breast support on dependent variables including vertical breast motion, absolute and relative joint negative work values. In the presence of a significant effect of breast support, a Tukey's post-hoc assessment was conducted to determine the source of significance. Significance was set at $p < 0.05$. Cohen's d estimates of effect sizes were also reported to further evaluate the effect of breast support on tot lower extremity joint negative work and absolute and relative joint contributions [40]. Cohen's d values were interpreted as follows: small, $d < 0.2$; moderate, $0.2 < d < 0.8$; large, $d > 0.8$. All statistical comparisons were conducted using Prism 8.3 (GraphPad Software, San Diego, CA).

Results

A significant main condition effect was observed for vertical breast displacement ($p < 0.001$). Post hoc analyses revealed that vertical breast displacement in the CON condition (4.3 ± 1.7 cm) was greater than in the LOW ($p < 0.001$; 3.0 ± 1.0 cm) and HIGH conditions ($p < 0.001$; 2.0 ± 0.7 cm) while the LOW condition was also associated with greater vertical breast displacement than the HIGH condition ($p < 0.001$).

Figure 1 presents individual and mean joint negative work values for the ankle, knee and hip while Table 2 presents absolute joint negative work values for the ankle, knee and hip as well as total lower extremity negative joint work. No effect of support was present for total negative work done by the lower extremity ($p = 0.759$). A significant main effect of support was observed for negative ankle joint work ($p < 0.001$, Figure 1). Post-hoc analyses revealed no differences between the CON and LOW conditions ($p = 0.185$); however, the HIGH condition was associated with less negative ankle joint work than either the CON ($p = 0.003$, $d = 0.23$) or LOW support conditions ($p = 0.003$, $d = 0.12$). No effect of support was observed for knee joint negative work ($p = 0.059$). A significant effect of support was observed for hip joint negative work ($p = 0.008$). Post-hoc tests revealed no differences between the CON and LOW support conditions ($p = 0.606$) while the HIGH support condition was associated with greater hip joint negative work than the CON ($p = 0.006$, $d = 0.29$) or LOW support conditions ($p = 0.002$, $d = 0.18$).

Figure 2 presents individual and mean relative joint contributions to total negative work for the ankle, knee and hip while Table 2 relative joint contributions to total negative work. A significant effect of breast support was observed for ankle joint relative contributions to total negative work ($p < 0.001$). Though no differences were observed between the CON and LOW conditions ($p = 0.94$), the CON and LOW conditions were associated with greater relative ankle contributions than the HIGH condition (CON: $p = 0.002$, $d = 0.35$; LOW: $p < 0.001$, $d = 0.25$). No effect of breast support was observed for knee joint relative contributions to total negative work ($p = 0.094$). A main effect of breast support was observed for hip joint relative contributions to total negative work ($p < 0.001$). Though no differences were observed between the CON and LOW support conditions ($p = 0.240$), the HIGH support condition was associated with greater hip joint relative contributions to total negative work than either the CON ($p < 0.001$, $d = 0.60$) or LOW ($p = 0.003$, $d = 0.33$) support conditions.

Discussion

The current study presents novel findings pertaining to the secondary effects of breast support on lower extremity negative joint work values during a landing task. These data address a sparsely investigated topic of the importance of sports bra support on biomechanics during sport-related movements. The current study included participants with self-reported bra sizes ranging from B- to D-Cup which may be more ecologically valid to understanding the effect of breast support on sport-related injury than previous research studies that have focused solely on large-breasted women (i.e. D-cup)[9,12,41]. The major findings of this study demonstrate that increasing the level of breast support was associated with altered lower extremity joint negative work values and a distal-to-proximal shift in relative joint contributions to lower extremity work.

Consistent with previous research, increasing levels of breast support were associated with reduced vertical breast displacements during the landing task [12]. It is suggested that breast displacement, which occurs at a significant time lag to trunk motion, presents a perturbation to trunk control during high velocity, sports-based movements. The results of the current study found reductions in vertical breast displacement in the HIGH compared to LOW and CON conditions which represents a reduction in the constraints placed on the neuromuscular system allowing a preferred movement strategy that may reduce the risk of injury to be implemented. The current study investigated landing biomechanics in which the forces applied to the skeleton were primarily in the vertical direction. As such, only vertical breast displacement was investigated. In other sport-based movements, such as running, previous data have demonstrated that mediolateral and anteroposterior breast motion is also reduced with increasing levels of breast support [12].

Increasing breast support was associated with a distal-to-proximal redistribution of joint negative work. The HIGH support condition was associated with significant reductions in ankle joint negative work with concomitant increases in hip joint negative work. Further, these shifts in joint negative work were mirrored in relative joint contributions to total lower extremity negative work. As such, the CON and LOW support conditions were characterized by a landing strategy that was more reliant upon ankle musculature for energy absorption compared to the HIGH support condition. Ankle-dominant landing strategies are indicative of landing biomechanics commonly associated with lower extremity injury.

Landing strategies characterized by greater ankle contributions to energy absorption are associated with greater stresses applied to the ACL [42,43]. Moreover, greater hip joint contribution to energy absorption in landing has been suggested to exhibit a protective effect on the ACL and a reduced risk of ACL injury [18,44]. Therefore, the current data suggest that the greater hip joint negative work and relative hip joint contributions to landing observed in the HIGH support condition may be associated with reductions in landing biomechanics commonly associated with ACL injury. Further, these data suggest that insufficient breast support result in landing strategies associated with increased ACL stress [42], greater knee-hip energy absorption ratios [18] and a greater risk of ACL injury.

The low levels of breast support (LOW and CON) did not result in the observed distal-to-proximal shift in joint negative work. The current findings demonstrate the lower extremity joint work profiles were similar between the CON and LOW support conditions. Though the HIGH support condition was associated with a potentially protective distal-to-proximal shift in joint work and joint contributions to energy dissipation, landing biomechanics in the LOW support condition were similar to landing biomechanics in the absence of any breast support. It should be noted that the vertical breast motion observed in the LOW support condition in the current study was similar to vertical breast motion previously reported in common high support sports bras manufactured by leading sportswear companies [45]. However, in the current study, vertical breast motion in the HIGH support condition was 33% less than the LOW support condition, and more than 50% less than previously reported values in high support sports bras manufactured by other sportswear companies [45]. These findings highlight the importance of identifying sports bras that provide the proper amount of support for each individual. Further, these findings suggest that improper sports bra selection and insufficient breast support may be associated with lower extremity biomechanical patterns that increase the risk of injury.

Though the current study presents novel findings of altered lower extremity biomechanics in response to increasing breast support, the authors acknowledge several limitations. Though the sample size was sufficient to provide a robust evaluation of the effects of breast support on lower limb joint work, the population was not homogenous with respect to breast size. The current sample included female recreational athletes with self-reported cup sizes ranging from B to D. It is suspected that landing kinetics were more effected in athletes with larger breasts due to the greater mass of the breasts as well as the passive nature of breast tissue. A second limitation of the current study pertains to the use of self-reported bra sizes for inclusion in the current study. Research has demonstrated that approximately 85% of women wear the wrong bra size [46]. Participant anthropometrics collected in the current study support those findings [47]. In the current study, only 15 of 35 participants had selected the proper bra size based on anthropometric measures of bust and ribcage circumferences. However, as this study did not parse participants into groups by breast size, the improper bra sizes did not affect research findings, but may have created additional variability and limit the generalizability. A third limitation of the current study pertains to the musculoskeletal model used to evaluate landing biomechanics. The model used to calculate inverse dynamics did not include a trunk segment. While the calculation of inverse dynamics at the ankle, knee and hip would not have been affected by trunk motion, it is known that trunk motion alters lower extremity muscle activation and lower extremity landing biomechanics [48,49]. Another limitation of the study pertains to the applicability of effect size calculations to within-subject designs. Effects size is calculated as the difference in means divided by the pooled variance. However, if the variance within each condition is large and a completely consistent effect occur across the group, the variance in the two observations will minimize the calculated effect size. This will result in lower calculated effect size and mask the overall effect of the intervention. This limitation leads to the selection of the current studies graphical figures (Figure1 and Figure 2) to depict the individual observations as well as the means and standard deviations. Future studies investigating the effects of breast support on lower extremity biomechanics would be benefited by the inclusion of a trunk segment.

The findings of this study demonstrate that increasing breast support is associated with a distal-to-proximal shift in joint negative work and relative joint contributions to total negative work in the lower extremity. The greater ankle joint contributions observed in the low support sports bra may be indicative of a landing strategy commonly associated with increased ACL stress and greater ACL injury risk. Moreover, the greater hip joint contributions associated with the high support sports bra may be indicative of lower ACL stresses and may have an ACL-protective effect. Therefore, breast support represents an easily addressable factor that influences landing biomechanics and contributes to potentially injurious movement biomechanics.

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Figure Captions

Figure 1. Individual and sample mean joint work values for the (A) ankle, (B) knee and (C) hip joints in the CON, LOW and HIGH support conditions during the double-limb landing task.

Figure 2. Individual and sample mean joint relative contributions for the (A) ankle, (B) knee and (C) hip joints in the CON, LOW and HIGH support conditions during the double-limb landing task.

Table 1. Anthropometric measures of study participants including the means for all participants and by self-reported cup size.

Group	N	Age (yrs)	Height (cm)	Mass (kg)	Bust (cm)	Ribcage (cm)
Total	35	23.8 ± 4.0	165.7 ± 5.6	61.6 ± 7.7	86.3 ± 4.9	74.0 ± 3.9
B-Cup	12	23.1 ± 4.1	166.4 ± 5.1	62.1 ± 8.6	85.0 ± 6.0	74.4 ± 4.8
C-Cup	13	24.5 ± 4.1	163.8 ± 5.7	61.4 ± 6.4	86.3 ± 3.0	74.7 ± 3.3
D-Cup	10	23.9 ± 4.1	167.3 ± 5.9	61.2 ± 8.8	87.9 ± 5.5	72.8 ± 3.7

Table 2. Mean values for ankle, knee and hip absolute joint work and relative joint contributions to total lower extremity work. Data are presented as mean ± SD.

Variable	**Joint**	**Control**	**Low**	**High**	**p-value**
Work (J)	Total	-4.81 ± 0.80	-4.73 ± 0.74	-4.82 ± 0.74	0.205
	Ankle	-1.12 ± 0.24	-1.10 ± 0.26	-1.06 ± 0.28 ^{a,b}	**0.005**
	Knee	-2.20 ± 0.32	-2.14 ± 0.29	-2.13 ± 0.28	0.074
	Hip	-1.48 ± 0.36	-1.50 ± 0.42	-1.59 ± 0.40 ^{a,b}	**0.007**
Work (% Total)	Ankle	23.4 ± 3.7	23.4 ± 5.0	21.9 ± 4.9 ^{a,b}	**0.020**
	Knee	45.7 ± 5.0	44.9 ± 5.3	44.6 ± 4.3	0.060
	Hip	30.7 ± 4.5	31.5 ± 4.9	33.4 ± 4.5 ^{a,b}	**0.047**

Note: ^{a} – denotes significant difference compared to CON, ^{b} – denotes significant difference compared to LOW.

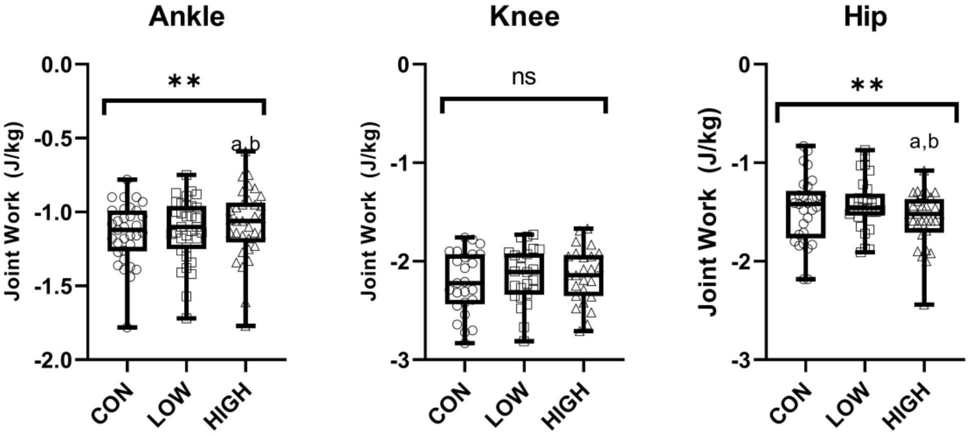

Figure 1. Individual and sample mean joint work values for the (A) ankle, (B) knee and (C) hip joints in the CON, LOW and HIGH support conditions during the double-limb landing task.

301x142mm (330 x 330 DPI)

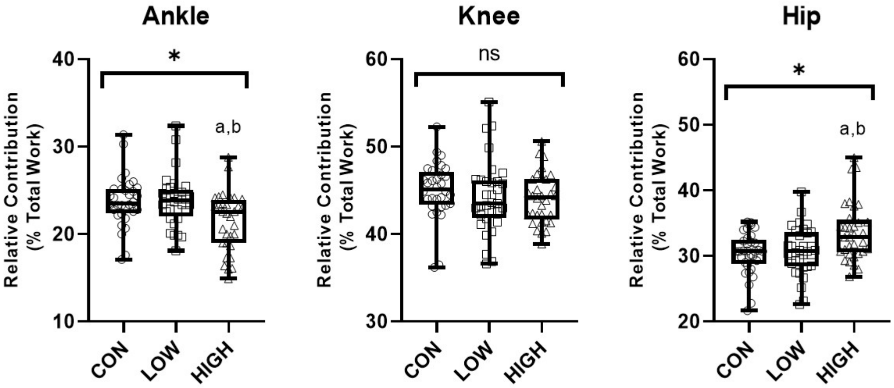

Figure 2. Individual and sample mean joint relative contributions for the (A) ankle, (B) knee and (C) hip joints in the CON, LOW and HIGH support conditions during the double-limb landing task.

338x190mm (96 x 96 DPI)

Reviewers' Comments to Author:
Reviewer: 1

Comments to the Author
I thank the authors for their previous revisions. I have no further comments.

Reviewer: 2

Comments to the Author
Thank you for your responses. I'm happy to recommend this manuscript for publication.

Reviewer: 3

Comments to the Author
General Comments
Overall, the authors did a great job addressing my comments about the paper. I still believe the paper will have a great impact, just some minor things to address! Otherwise, I think it's acceptable for publication.

INTRODUCTION

1. Reviewer Response: Line 30: "…and altered hormonal profiles". Altered compared to what? I would refrain from using altered as it suggests that males are the "normal" or "baseline". More, I understand the inclusion of hormonal profiles due to their importance to maturation, particularly of breast tissue. But I think including it in the first sentence of this paragraph imparts a level of importance of this that isn't really reflected in the paper.
Author Response: The authors thank the reviewer for all their responses. We have removed the term "altered" from the sentence to better indicate that there are sex differences in hormonal profiles but not comparative to males as a "normal" or "baseline". The sentence now reads: *"Sex-based differences in anatomical morphology 3, 4 and hormonal profiles 5, 6 have been suggested to contribute to an increased risk of ACL injury in female compared to male athletes."*

2. Reviewer Response: Line 32-33: "Maturation has also…" I believe this sentence can be removed. Taking these two recommendations together, I suggest you change the wording on Line 30 to say "Sex-based differences in anatomical morphology, including those associated with hormonal profiles (e.g., breast tissue),…" then go in to something similar to, "In fact, breast development is a sex-specific trait that emerges with maturation of hormonal profiles in females."
Author Response: The authors have removed the sentence mentioning maturation and its influence on ACL injury in female athletes. The text now reads, "*Sex-based differences in anatomical morphology* [3,4] *and hormonal profiles* [5,6] *have been suggested to contribute to an increased risk of ACL injury in female compared to male athletes. Breast development is a sex-*

specific trait that emerges during maturation [7] *that has been shown to alter movement biomechanics*.”

3. Reviewer Response: Lines 38-39: Can put the bra conditions in parenthesis. “…increasing breast support (no support, low support, and high support) has been shown…”
Author Response: The authors have now put the bra conditions in parathesis as the reviewer suggests. However, we have also included the words “sports bras” at the end of the support condition to support the readers understanding that sports bras were used to change the amount of support in the different conditions. The sentence now reads, “*In treadmill running, greater breast support (low support and high support sports bra) has been shown to reduce breast lag resulting in altered trunk, pelvis and upper extremity kinematics*[8].”

4. Reviewer Response: Lines 40 – 45: I also think you can expand on what these altered mechanical profiles are and what that means. Were trunk/pelvic/upper extremity kinematics good or bad and why? Are the altered spatiotemporal parameters good or bad? Don’t have to say too much, could even tie it to the sentence about running economy.
Author Response: The authors have expanded on the importance and relevance of changes in kinematics due to influencing breast support. We have also re-organized the text to better maintain the flow of thoughts. The text now reads, “*The alterations of trunk, pelvis, and upper extremity kinematics with high breast support has been shown to increase energy preservation and is beneficial to running performance for female athletes during running*[8]*. Data reported by Fong & Powell* [10] *further support the notion that increasing breast support improves running performance by demonstrating that greater breast support is associated with reduced oxygen consumption and greater running economy during treadmill running. Mechanically, during over running, increased breast support has been associated with greater stride lengths, reduced cadence, greater vertical trunk displacements* [11] *and greater knee joint stiffness* [12]*. These findings demonstrate that breast support not only affects breast motion but has secondary effects lower extremity biomechanics and running performance* [8,10-12]*.”*

5. Reviewer Response: Line 46: change “exist” to “are reported”. Try to stay away from dichotomous wording.
Author Response: The authors have removed “exist” to “are reported”. The sentence now reads, “*Sex-based differences in lower extremity biomechanics patterns have been reported during sport-relevant movements such as jumping, landing and cutting 12-16.”*

6. Reviewer Response: Line 48: Cite the study where female athletes utilize unique landing biomechanics.
Author Response: The authors have cited the landing studies. The sentence now reads, “*Evidence has demonstrated that female athletes utilize unique landing biomechanics compared to male athletes* [12,14,16].”

7. Reviewer Response: Line 50: Cite the study about anthropometry and movement patterns. This also seems vague. What anthropometric measures? What distinct movement patterns – landing? What injuries, what rates?
Author Response: The authors have now included citations. The anthropometric variables we refer to include Q-angle, pelvis width, tibial notch size, and ligament laxity, which differ

between female and male athletes. These variables are associated with changes in movements patterns that result in increased risk of injury for female athletes. While these anthropometric variables are important, we want to focus on biomechanical risk factors of injury rather than non-modifiable risk factors including the following anthropometric variables. Furthermore, these anthropometric variables are associated with multiple, different types of injury. For example, Q-angle may also influence patellofemoral pain syndrome. The current manuscript focuses on ACL injury specifically; however, anthropometric variables and changes in movement pattern are not limited to only ACL injury. The sentence now reads, "*Moreover, sex-based differences in anthropometry have been implicated in these distinct movement patterns as well as greater injury rates in female compared to male athletes* [18-22]."

8. Reviewer Response: Line 51: "…greater vertical ground reaction forces (GRF) magnitudes and peak dorsiflexion angles, and smaller peak knee flexion angles…"
Author Response: The sentences reads, "In landing, female athletes exhibit greater vertical ground reaction forces (GRF) magnitudes, greater peak dorsiflexion angles and smaller peak knee flexion angles compared to male athletes [14, 17, 18]."

9. Reviewer Response: Line 54: Remove "At the knee", start with "Female…"
Author Response: The authors have started the sentence with "Female…" instead of "At the knee…". The text now reads, "*Female athletes also exhibit greater initial plantarflexion, greater ankle joint ranges of motion, greater ankle joint velocities and greater energy absorption than male athletes* [12, 19]."

10. Reviewer Response: Line 59 – 60: remove the words "than male athletes", you're not using comparative words preceding this. Cite paper(s) associated with the landing patterns.
Author Response: The authors have removed the words "than male athletes", and the sentence now reads, "Further, female athletes absorb less energy at the hip as evidenced by smaller relative hip joint contributions to landing [12]."

11. Reviewer Response: Line 60: add the word dominant after hip.
Author Response: The authors have added the word dominant after hip. The sentence now reads, "*The adoption of a preferred hip dominant strategy in collegiate female athletes, more closely mimicking landing patterns of male athletes…*"

METHODS

12. Reviewer Response: Line 87: I feel like you can remove the sentence about the effect size of 0.5 as it is later included (line 90).
Author Response: The authors have removed the sentence about the effect size as it is included in the following sentence.

13. Reviewer Response: Make sure you add whether or not participants signed an informed consent prior to participation

Author Response: This information is presented in line 100 of the text and reads, "The experimental protocol was approved by the University Institutional Review Board and all participants provided written informed consent prior to study participation."

14. Reviewer Response: Line 106: Change "the skeleton was modelled" to "A kinematic model was built using 14 mm…"
Author Response: The sentence now reads, "*A kinematic model was built using 14 mm retroreflective markers and included the pelvis as well as bilateral thigh, shank and foot segments.*"

15. Reviewer Response: Lines 107 – 108: change instances of "right and left" to bilateral.
Author Response: The authors have changed both instances of "right and left" to bilateral. The sentences now read, "*A kinematic model was built using 14 mm retroreflective markers and included the pelvis as well bilateral thigh, shank and foot segments. Anatomical markers were placed over the bilateral anterior superior iliac spines, posterior superior iliac spines, iliac crest and trochanters.*"

16. Reviewer Response: Methods may benefit from a table that lists tracking and calibration markers, what segments they defined, etc.
Author Response: The authors thank the reviewer for their feedback. However, we have included this information within the text of the methods section and do not feel a table with the same information is a necessary addition to the manuscript.

17. Reviewer Response: How many DoF was the model?
Author Response: The model had 6 DoF.

18. Reviewer Response: Line 127: was the 0.40m drop off of a box?
Author Response: The authors have clarified that the step-off landing was completed from a 0.40 m box. The sentence now reads, "*Each participant then performed five successful step-off landing trials from a 0.40 m box in three different breast support conditions…*".

19. Reviewer Response: Line 146: As you said in the introduction that there is lag between the torso and the breast tissue, is there a chance that the minimum breast position from IC – Pk Knee Flx is not the minimum position? Is there a chance that the minimum breast position during stance occurs after peak knee flexion? Just something to consider!
Author Response: It is possible that the minimum vertical position of the breast relative to the torso does occur after peak knee flexion in landing. Specifically, as the torso begins to move vertically upward during the second half of the landing cycle (for subsequent movements in ecologically valid athletic tasks), the breast tissue may undergo significant strain or make contact with the anterior trunk wall (termed "breast slap"). However, mechanically, the lower extremity has transitioned from load attenuation or force absorption to a force generation phase. Given our focus was the load attenuation phase of the landing, the breast motion beyond peak knee flexion would not have influenced the load attenuation strategies. However, future evaluation of breast biomechanics relative to the trunk with specific emphasis on the role of lag in altering trunk and pelvis motion during sport-related activities such as running, landing and cutting (change of direction) will examine this relationship more closely. We thank the reviewer for this comment.

RESULTS

20. Reviewer Response: I always suggest starting with interaction effects prior to going to main effects unless there aren't any interactions (but you have some!)
Author Response: Based on our statistical design (1 x 3 repeated measures ANOVA), it is not possible to have any interactions. Therefore, we only present main effects and post-hoc pairwise analyses of those significant main effects. We report the joint-level changes in negative work (a series of 1 x 3 repeated measures ANOVAs) in the same paragraph; however, we did not conduct a 3 x 3 repeated measures ANOVA. We apologize if the inclusion of all negative work findings (all joints and total) within a single paragraph may have led to confusion.

DICSUSSION

21. Reviewer Response: Line 202: Suggest changing "large-breasted women" to "larger breasts" and parenthetically stating what size is implied by that (e.g., C cup or above).
Author Response: The authors thank the reviewer for the clarification. Majority of previous research has investigated the influence of breast support with subject inclusion criteria limited to only females with a D-cup breast size or larger. However, our research has expanded the inclusion criteria to include females with a breast size of B- to D-cup. Further, most previous research has included the description of participants as "large-breasted women", therefore, for consistency, we have adopted similar verbiage. The sentence now reads, "*The current study included participants with self-reported bra sizes ranging from B- to D-Cup which may be more ecologically valid to understanding the effect of breast support on sport-related injury than previous research studies that have focused solely on large-breasted women (i.e. D-cup)*[9, 34, 35]."

22. Reviewer Response: Line 206 – 208: This is a good inclusion!! Might be a good idea to add to the intro, adds a so-what that might be missing when you previously talk about breast motion.
Author Response: The authors have included a few sentences from lines 37-39 about the consequence of breast-body time lag on trunk control which may result in changes in upper and lower extremity kinematics. The text now reads, "*Moreover, breast motion occurs with a significant time lag compared to torso motion evidenced by a delay in onset of movement of the passive breast tissue relative to the trunk* [9]*. It is suggested that this breast-body time lag presents a perturbation to trunk control during sports-based movements. These perturbations are purported to have secondary influences on both upper and lower extremity kinematics* [8,10-12]."

23. Reviewer Response: Line 223: After you talk about the reduced reliance on the ankle in HIGH compared to CON/LOW, add a short sentence about WHY this is important. This makes the transition to the next paragraph a little more seamless.
Author Response: The authors have added a sentence at the end of the paragraph about the significance of an ankle-dominant landing strategy as it relates to lower extremity injury. The sentence reads, "*Ankle-dominant landing strategies are indicative of landing biomechanics commonly associated with lower extremity injury.*" The next paragraph mentions the significance of an ankle versus hip dominant landing strategy as it relates to ACL injury, specifically. This

change should make the text more seamless.

That’s it! Good work! I truly do enjoy this paper. Thank you for your time and work on this!