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Surface Accelerometer Fixation Method Affects Leg Soft Tissue Motion Following Heel Impacts

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Abstract

Surface-mounted accelerometers (SMA) secured tightly to body segments with an elastic strap, are commonly used to quantify the impact response of bone. However, the effect that this type of fixation has on segment soft tissue motion relative to bone has yet to be determined. Heel impacts were collected from 20 participants using a human pendulum apparatus, with (strap) and without (no strap) a SMA attached to the proximal tibia. Leg soft tissue motion was quantified using digital image analysis software which monitored positions of skin markers from a series of high speed photographs. The strap was found to alter the natural physiological motion of the soft tissue, with significant displacement, velocity and sex differences occurring within the most proximal regions. Future research should evaluate alternative methods for quantifying bone and soft tissue response to impact concurrently, to advance our understanding of impact-related injury mechanisms.

Keywords: soft tissue motion, lower extremity, impact, accelerometer, human pendulum

1. Introduction

Walking, running and jumping are activities characterized by repetitive impacts between the feet and the ground. Shock waves generated from these impacts propagate through, and are attenuated by, the body's tissues both actively (e.g., via muscle contraction) (Mercer, Bates, Dufek & Hreljac, 2003a) and passively (e.g., via the motion of soft tissues relative to bone) as they travel proximally away from the impact site (Dufek, Mercer & Griffin, 2009). Because impact loading of this nature has been linked to degenerative joint diseases and overuse injuries, including stress fractures (Milgrom et al., 1985; Hame, Lafemina, McAllister, Scaadt & Doret, 2004), shin splints (Detmer, 1986), osteoarthritis and cartilage breakdown (Simon, Radin, Paul & Rose, 1972; Radin, Orr, Kelman, Paul & Rose, 1982), as well as low back pain (Voloshin & Wosk, 1982), quantifying the impact response of the body's tissues has received considerable attention in the literature. The response of bone to impact in the lower extremities has been measured using bone-mounted (Lafortune, Henning & Valiant, 1995) and surface-mounted (Derrick, Hamill & Caldwell, 1998; Andrews & Dowling, 2000; Mercer, Devita, Derrick & Bates, 2003b; Holmes & Andrews, 2006; Duquette & Andrews, 2010a, 2010b; Schinkel-Ivy, Burkhart & Andrews, 2012) accelerometers.

While bone-mounted accelerometers directly measure the response of the bone, they are not practical for most *in vivo* studies because of the invasiveness of the methods required to rigidly affix them (Gao & Zheng, 2008). Consequently, surface-mounted accelerometers (SMA) have been used extensively to quantify the impact response of bone and have been found to be a valid and practical alternative (Kavanagh, Morrison, James & Barrett, 2006; Liikavainio et al, 2007) if a low mass accelerometer (Kim, Voloshin, Johnson, Simkin, 1993) is tightly attached to the skin (Ziegert & Lewis, 1979) with a thin layer of soft tissue between the bone and accelerometer (Saha & Lakes, 1977) to minimize soft tissue motion artifact (Akbarshahi et al., 2010; Pain & Challis, 2002). Securing SMAs over bone in the leg is commonly accomplished at the proximal tibia (Andrews & Dowling, 2000; Schinkel-Ivy, et al., 2012) using elastic or compression straps tightened to the participant's tolerance, without causing discomfort (Shorten & Winslow, 1992; Kim et al., 1993; Derrick et al., 1998; Andrews & Dowling, 2000; Mercer et al., 2003a, 2003b; Schinkel-Ivy et al., 2012).

Numerous studies have shown that accounting for the effects of soft tissue motion relative to bone is fundamental when modeling the response of the body to impacts (Gruber, Ruder, Denoth & Schneider, 1998; Pain & Challis, 2001, 2002, 2006; Gittoes, Brewin & Kerwin, 2006). While differences in the tibial response to impact for males and females (Schinkel-Ivy et al., 2012) have been attributed in part to differences in leg soft tissue composition between the sexes (Burkhart, Arthurs & Andrews, 2008), it is unknown what effect sex might have on the motion of the soft tissue. Therefore, being able to accurately quantify the response of both bone and soft tissue resulting from impact simultaneously, without interfering with the relative motion of each tissue via the instrumentation utilized, appears to be critical if our understanding of how tissues affect shock propagation is to be advanced for both men and women. To the authors' knowledge, the effect that an external strap, which is typically used to affix a SMA to measure the impact response of bone, has on the soft tissue motion of the leg, has yet to be quantified in the literature. If soft tissue motion following impact is altered by a strap used to measure bone acceleration concurrently, then any measures of shock attenuation associated with soft tissue motion may also be negatively affected, which could alter estimates of impact-related injury risk.

Therefore, the purpose of this study was to quantify the effect that typical SMA fixation with an external strap has on the motion of the soft tissues of the leg following simulated running impacts using a human pendulum approach.

2. Methods

2.1 Participants

Twenty healthy young adults (9 male, 11 female; mean age 23.7 ± 2.4 years; mean height 1.7 ± 0.1 m; mean body mass 71.0 ± 16.7 kg) who were free of pain and injury in the lower extremity and back over the previous year (as indicated on a general health questionnaire) participated in this study. All procedures were approved by the Research Ethics Board at the University of Windsor and all participants provided signed consent prior to testing.

2.2 Apparatus and Procedures

Prior to impact testing, two flexible, clear plastic stencils with holes were used to produce a square grid pattern of black markers (0.5 cm circumference; inter-marker distance of 2 cm) on the skin of the shaved right leg of each participant, using a permanent black marker (Figure 1). The stencils were wrapped around the leg following careful alignment with anatomical landmarks (tibial crest and medial malleolus) to ensure marker application consistency between participants.

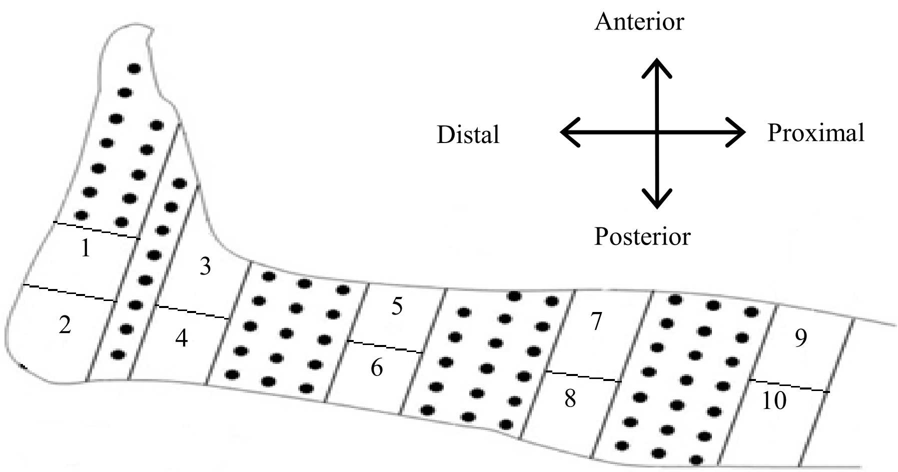

Figure 1. Schematic diagram of the marker grid of dots arranged in 2x2 cm squares on the right leg and foot. The 10 regions of the leg and foot analyzed are indicated (dots not shown in these regions).

Participants underwent heel impacts (described below) in two experimental conditions: "strap" (with a SMA attached to the proximal leg) and "no strap" (no SMA attached). In the strap condition, a triaxial accelerometer (MMA3201D, Freescale Semiconductor, Inc, Ottawa ON, Canada; range 50 g) was attached to the skin just medial to the tibial tuberosity on the right leg using double-sided tape. The SMA was securely affixed using an elastic strap that applied a normal preload of approximately 45 N to the SMA (Andrews & Dowling, 2000) (Figure 2A). In the no strap condition, no instrumentation was attached to the leg (Figure 2B).

A human pendulum apparatus consisting of a rigid steel frame (190.5 x 52.5 cm) and canvas bed (Flynn, Holmes & Andrews, 2004; Holmes & Andrews, 2006; Duquette & Andrews, 2010a, 2010b; Schinkel-Ivy et al., 2012) was used to deliver three heel impacts to the right foot of each participant in each condition (i.e., strap and no strap). Impacts occurred with a vertically oriented force platform (AMTI-OR6-6-1000, A-Tech Instruments Ltd., Scarborough, ON, Canada) which was mounted on steel bars in a grid-like pattern on the laboratory wall (impact apparatus). A velocity transducer (Celesco DV30J, Don Mills, ON, Canada) was attached to the trailing end of the pendulum and a high speed camera (Fastec Imaging, San Diego CA, Troubleshooter HR; 1000 frames/s, 640 x 480 pixels^2), situated perpendicular to the direction of travel, was used to capture the motion of the foot and leg soft tissue at impact. Lying supine, participants were firmly secured to the pendulum using straps across their hips and right thigh, with their right leg extended beyond the front edge of the pendulum frame, and left leg flexed at the knee (to keep it out of the camera view). Pendulum pull back distance for each participant was determined via test impacts such that the impact velocity (1.0 m/s -1.15 m/s) and force (1.8-2.8 times body weight) were similar to those experiences during running (Cavanagh & Lafortune, 1980; Flynn et al., 2004; Holmes & Andrews, 2006; Duquette & Andrews, 2010a, 2010b; Schinkel-Ivy et al., 2012).

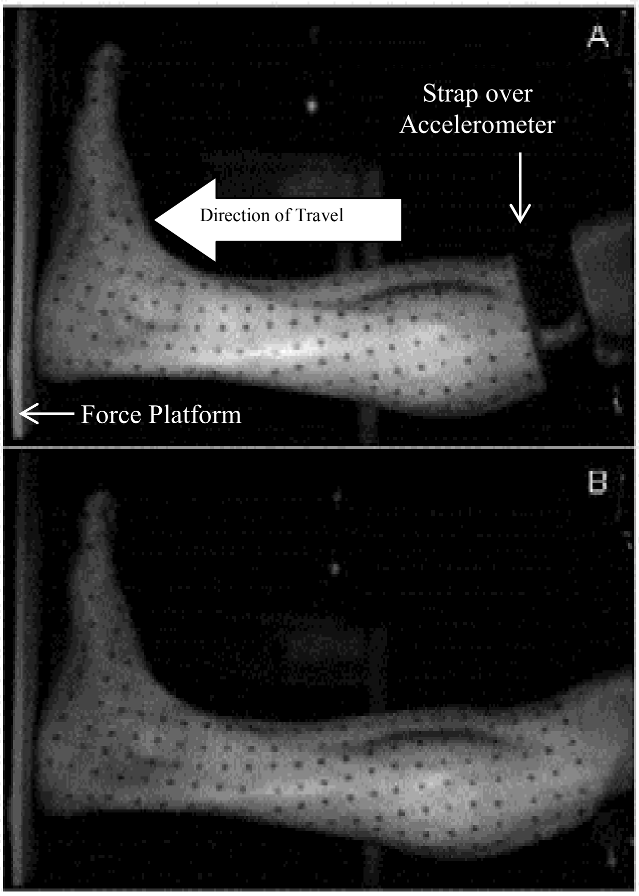

Figure 2: Picture of the (A) strap and (B) no strap setup for one participant at the point of impact with the force platform.

2.3 Data Analysis

Prior to analysis, the series of high speed photographs were used for length calibration, utilizing a calibration unit of 6 cm between three markers. Image filtering techniques were used such that automatic tracking of markers was obtainable; photographs were reversed (black to white and white to black) and a series of filters (5x5 Laplacian high pass filter & despeckle filter) were applied to optimize image quality and marker contrast. All photographs were analysed using ProAnalyst® motion tracking software (ProAnalyst®; Xcitex, Cambridge, MA), from the point just prior to heel impact, until the leg was stationary (approximately 150 ms to 250 ms in duration).

Markers within ten regions on the leg and foot (representing anterior and posterior areas at various locations between the heel and knee joint) (Figure 1) were automatically tracked using ProAnalyst® (search region multiplier - 250 %; threshold tolerance - 0.75) for the series of photographs, between impact and movement cessation. Marker displacements in the proximal, distal, anterior and posterior directions (Figure 1) were recorded. Data from one representative marker in each region were imported into a customized LabVIEW® (LabVIEW® 2010, National Instruments, Austin TX) program and then filtered at 35 Hz with a dual pass, 4th order Butterworth filter (Brydges, 2013). Peak marker velocities in each direction were then calculated via differentiation of the filtered displacement data. This method of selecting and analyzing marker data using this experimental setup has been shown to have excellent (i.e., ICC> 0.75), between- and within-measurer reliability (Brydges, Burkhart, Altenhof & Andrews, 2012).

Three-way (2 sex x 2 strap conditions (strap vs. no-strap) x 10 leg regions), mixed ANOVAs with sex as the between-subject factor, were conducted on the soft tissue displacement and velocity data in each direction (proximal, distal, anterior, posterior) (alpha set at 0.05). Simple effects tests were performed on significant interactions for condition (strap and no strap) and sex (male and female) ($p<0.05$). A one-way analysis was performed to further indicate significance by region for both displacement and velocity data in each direction. Tukey's HSD test was performed on all significant one-way ANOVA analyses to determine where the significant interactions occurred. All statistical tests were performed with SPSS 19 (IBM SPSS statistics, IBM Corporation, Somers NY).

3. Results

3.1Displacement

Overall, there was a trend towards increasing soft tissue displacement in all directions from the distal to proximal regions regardless of condition (strap vs. no strap) (Figure 3). Mean displacement values between the strap and no strap conditions only differed significantly in the distal and anterior directions for regions 8-10 and region 10, respectively (Figure 3B and 3C); the most proximal regions closest to the strap. Within regions 8 through 10 in the distal direction, the mean displacement ranged between 1.87 cm and 2.14 cm in the no strap condition compared to only 1.62 cm and 1.83 cm in the strap condition (Figure 3B). In the anterior direction, the mean displacement in the no strap condition for regions 8, 9 and 10 was approximately 34% greater than in the strap condition (0.35 cm vs. 0.23 cm) (Figure 3C).

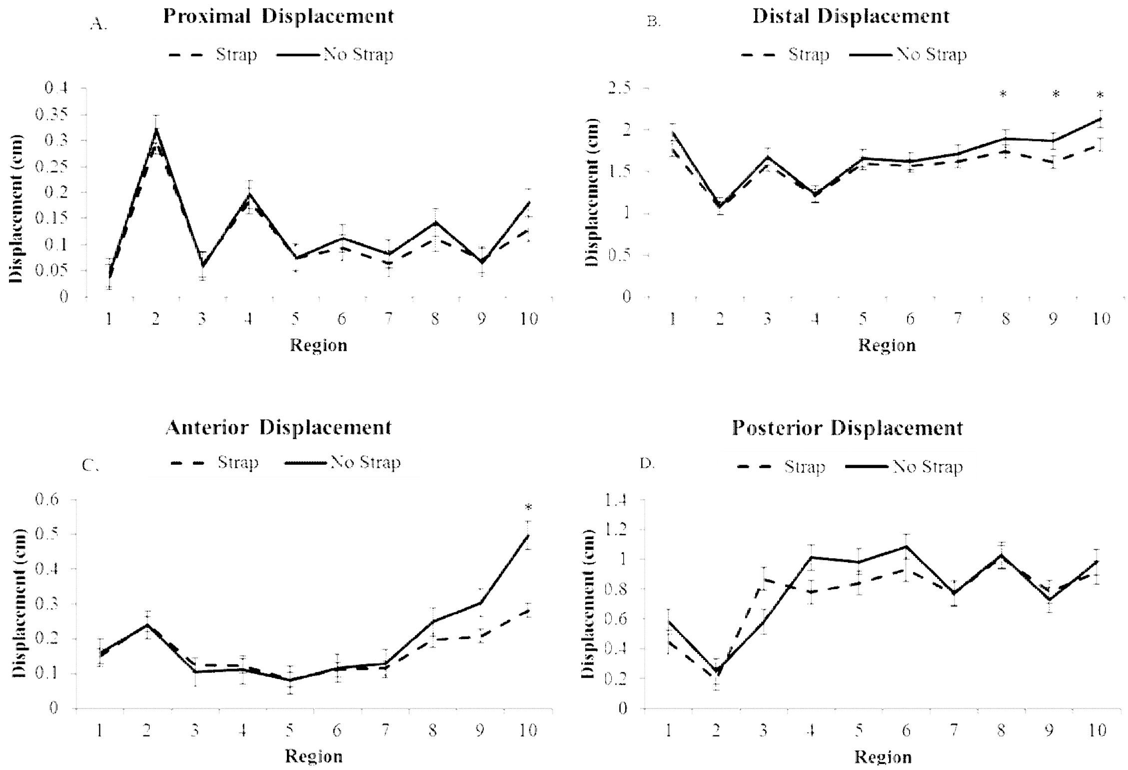

Figure 3: Soft tissue displacements in (A) proximal, (B) distal, (C) anterior and (D) posterior directions across all regions for strap and no strap conditions (*$p<0.05$).

3.2Velocity

Consistent with the displacement results, mean soft tissue velocities generally increased from distal to proximal regions (Figure 4). In addition, mean velocity values between the strap and no strap conditions only differed significantly in the proximal, distal and anterior directions for the most proximal regions in the segment (Figure 4A, B, C, respectively). In regions 9 and 10, mean soft tissue velocities were always greater in the no strap condition compared to the strap condition, with differences of 15.0 cm/s, 7.3 cm/s and 17.2 cm/s in the proximal, distal and anterior directions. The soft tissue velocities in the distal direction were the greatest overall compared to the other directions, with mean values across all regions and conditions being 64%, 67%, and 48% greater than those in the proximal, anterior and posterior direction, respectively.

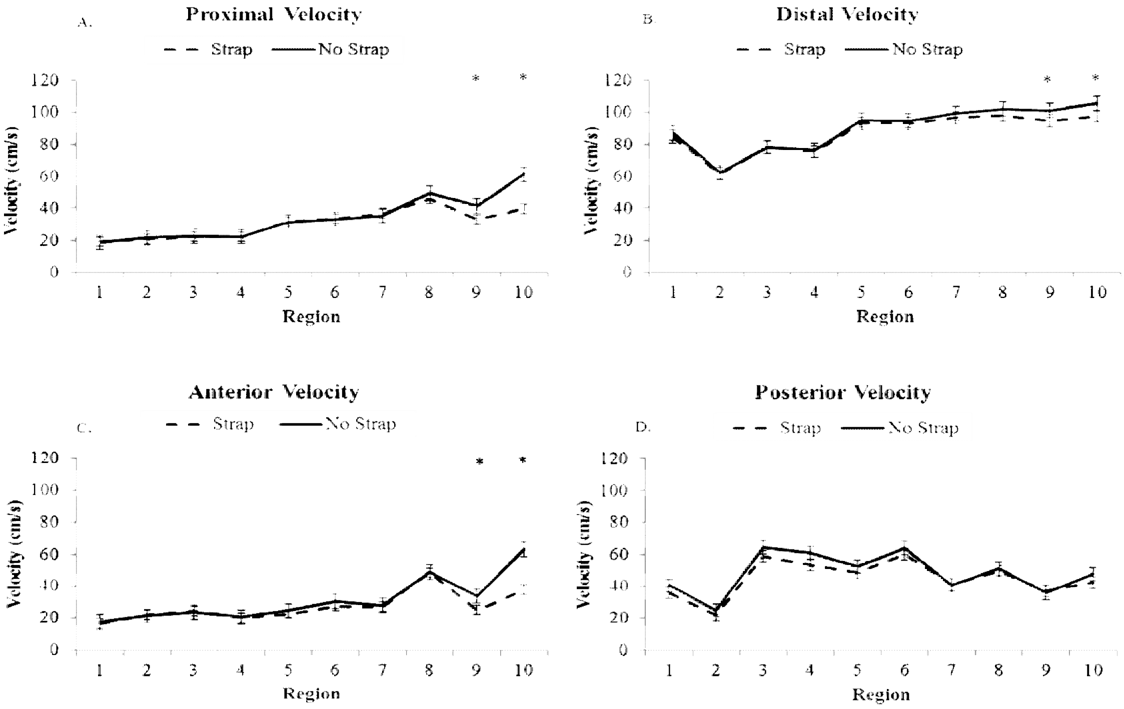

Figure 4: Soft tissue velocities in (A) proximal, (B) distal, (C) anterior and (D) posterior directions across all regions for strap and no strap conditions (*p<0.05).

3.3Sex

A significant interaction was found between condition and sex on distal soft tissue displacement (Figure 5). Males and females both demonstrated equal or greater distal displacements without the strap compared to when the strap was used across all regions. However, males in general consistently exhibited greater soft tissue displacement compared to females throughout the most distal regions. Within the proximal regions (5-9), the trend for the no strap conditions differed significantly between the sexes, ranging from 1.69 cm-1.99 cm for males and 1.56 cm-1.86 cm for females. There was a significant main effect of sex on mean proximal soft tissue velocity. Females produced greater soft tissue velocities then males in the regions in the most proximal half of the leg [regions 5-10: 35.1 cm/s - 59.0 cm/s (females) vs. 27.6 cm - 40.5 cm/s (males)]. A significant interaction was found between region and sex on posterior displacement, distal displacement, posterior velocity and proximal velocity. For posterior displacement and velocity, males exhibited higher values than females between regions 1-7 (0.91 cm and 55.5 cm/s compared to 0.63 cm and 41.3 cm/s), whereas females' values were greater in regions 8-10 (0.99 cm and 46.9 cm/s compared to 0.80 cm and 40.2 cm/s).

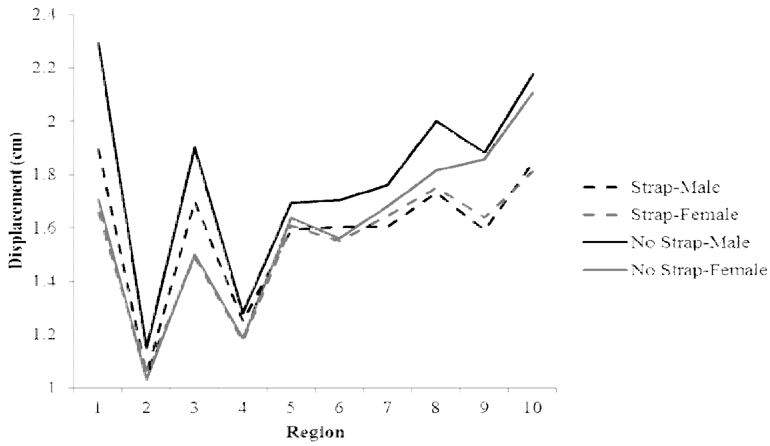

Figure 5: Condition (strap and no strap) effects for sex on distal displacement (*p<0.05).

4. Discussion

This study showed that the addition of a strap to secure a surface-mounted accelerometer to the proximal tibia - a commonly used technique to measure tibial impact response during simulated running activities (Derrick et al., 1998; Mercer et al., 2003b; Holmes & Andrews, 2006; Duquette & Andrews, 2010b; Schinkel-Ivy et al., 2012) - significantly reduced the displacement and velocity of the leg soft tissue in several directions, and therefore interfered with the tissue's natural motion following impact. This conclusion is consistent with Leardini, Chiari, Della Croce & Cappozzo (2005), who suggested that external fixation devices, while accurate, may affect the natural tissue motion. Quantifying the effect that surface fixation techniques have on soft tissue motion is an important consideration. If natural soft tissue motion is negatively affected by the method used to measure it, the capacity of the tissue to attenuate impact shock may also be affected. This could lead to incorrect conclusions regarding the relative role that soft tissue motion plays and will limit our understanding of how tissues interact to attenuate shock as it propagates through the body (Pain & Challis, 2002, Gittoes et al., 2006).

In most cases, soft tissue motion increased from distal to proximal regions of the leg. Differences in soft tissue motion between the strap and no strap conditions also varied significantly as a function of leg region. The greatest effect on soft tissue motion from the strap was found in regions with the greatest soft tissue mass; the most proximal regions closest to the strap (i.e., regions 8-10). Conversely, differences in soft tissue motion due to the strap in the distal regions of the leg were not significant. These findings are consistent with the fact that there is less soft tissue in the distal regions of the leg, as identified in previous literature by Clarys & Marfell-Jones (1986).

Significant differences in soft tissue motion between the strap and no strap conditions were consistently shown in the anterior and distal directions. The horizontal orientation and direction of travel of the pendulum used to initiate the heel impacts in this study may have contributed to these findings. Displacement and velocity in the distal direction were found to be considerably greater than in the other directions on average. The soft tissue rapidly accelerated towards the foot once the impact between the heel and the force platform occurred (Figure 2), a movement in the distal direction. The soft tissue then rebounded in the proximal direction, but the magnitude of the shock created was lessened due to the visco-elastic nature of the soft tissue (Gittoes et al., 2006) as it deformed, and moved relative to the underlying bone. The restriction imposed on the soft tissues of the most proximal regions of the leg by the strap, further damped the motion of the soft tissues as they rebounded following the impact.

While previous studies have investigated sex differences in leg tissue composition (Burkhart, Arthurs & Andrews, 2008) and the effect that these differences have on tibial response to impact (Schinkel-Ivy et al., 2012), differences in leg soft tissue motion between the sexes caused by surface-mounted accelerometer fixation, has not been reported to date. A significant main effect of sex was only found on proximal velocity, with females consistently demonstrating higher velocity outputs in this direction for regions 5-10. Although not statistically significant, females also consistently demonstrated greater soft tissue motion than males in the most proximal regions (8-10) near the SMA for posterior displacement and velocity. These results may be attributed in part to the significant differences in leg tissue composition between the sexes (Lemieux, Prud'homme, Bouchard, Tremblay & Despres, 1993; Ross et al., 1994; Ogle et al., 1995; Schinkel-Ivy et al., 2012). For example, Schinkel-Ivy et al. (2012) reported that females had significantly more fat mass than males within the leg segment. The lower density of fat tissue compared to other soft tissues, which is the underlying principle in body composition tests (Hamdy, Porramatikul & Al-Ozairi, 2006), may have a differential effect on the response of the overall soft tissue package after impact for women compared to men. While it is important to quantify differences in tissue composition, and the effects that these differences may have on impact response and injury prevention between the sexes, the soft tissue displacements and velocities reported for the sexes in the current study must be taken in context, and the scope of the results acknowledged, in order to drive future work in this area.

The results of this study demonstrated that leg soft tissue motion can be altered by using the strap technique described herein. However, it must be noted that the significant differences in soft tissue motion between the strap and no strap conditions were limited to the most proximal regions of the leg, near to where the strap was located. The effect that the strap had on soft tissue motion in the distal three quarters of the segment was negligible and not statistically significant in most cases. Future research should evaluate the effect of affixing a surface-mounted accelerometer in other anatomical locations on the leg, using the current strap technique. Although the current study utilized the same procedures reported previously, with respect to fixation method and location (Andrews & Dowling, 2000; Holmes & Andrews, 2006; Duquette & Andrews, 2010a, 2010b; Schinkel-Ivy et al., 2012), there may be alternate mounting locations on the tibia that result in less interference with proximal soft tissue motion. In addition, this study only analyzed impacts in the horizontal direction, and only quantified soft tissue motion in two dimensions; two important differences compared to typical running and landing activities in sport and recreation. Evaluating a broader range of activities with more sophisticated camera systems in three dimensions may result in different soft tissue motion magnitudes and direction effects compared to those reported here and could help to explain the differences in soft tissue motion recorded for men and women.

4.1Conclusions

Surface-mounted accelerometry has been shown to provide valuable information about segmental impact response. The results of this study show that affixing a surface-mounted accelerometer using a strap to quantify the response of the tibia to heel impacts, can negatively affect natural leg soft tissue motion; motion that has been shown to be very important for shock attenuation. The magnitude of the effect that the strap has on soft tissue motion, and therefore estimates of shock attenuation, is likely dependent to some degree on the amount and composition of soft tissue located in the proximal leg. Utilizing a surface-mounted accelerometer to measure bone acceleration is still a valid and reliable method. However, simultaneous measurement of bone and tissue response using surface accelerometry may interfere with the natural motion of the soft tissue of the leg. Accurate tracking of both bone and soft tissue motion concurrently using massless skin markers, similar to those used in this study, may be a viable option to eliminate the negative effects of surface accelerometer fixation using straps, but would require much higher frame rates than used in the current study. Future research in this area appears warranted given the importance of tissue motion following impact as a mechanism for shock attenuation and lower extremity injury prevention.

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