USING A WIRELESS INERTIAL SENSOR TO MEASURE TIBIAL SHOCK DURING RUNNING: AGREEMENT WITH A SKIN MOUNTED SENSOR

Leona Brayne[1], Andy Barnes[2], Ben Heller[1] and Jon Wheat[1]
Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, England[1]
Academy of Sport and Physical Activity, Sheffield Hallam University, Sheffield, England[2]

Monitoring and feedback of tibial shock using wireless skin mounted sensors could reduce the risk of injury in runners. The purpose of this study was to assess the agreement between a wireless sensor and a skin mounted accelerometer in measuring peak tibial acceleration during running. A skin mounted laboratory standard accelerometer was mounted to a wireless inertial sensor and attached to the tibia. Peak positive tibial accelerations of 13 participants were compared at 2.5 ms^{-1}, 3.5 ms^{-1} and 4.5 ms^{-1}. Intraclass correlation coefficient demonstrated good agreement. Limits of agreement showed accuracy to within 1.2 – 1.65 *g.* The inertial sensor can be used as a tool to measure peak tibial accelerations during running for the purpose of real-time feedback in a gait training system.

KEYWORDS: Tibial shock, real-time feedback, running.

INTRODUCTION: Stress fractures are common among runners, especially at the tibia (Crowell, Milner, Hamill, & Davis, 2010). Tibial stress injuries represent a significant problem in runners as the rehabilitation period can be anything from 6-12 weeks (Harrast & Colonno, 2010). Higher peak tibial shock has been found to be a strong risk factor for injury in both prospective (Davis, Milner, & Hamill, 2004) and retrospective studies (Pohl, Mullineaux, Milner, Hamill, & Davis, 2008). Modifying peak tibial shock might decrease a runner's risk of a tibial stress injury.

In treadmill running, reductions in peak tibial shock of almost 50 % (measured using a wired accelerometer) have been reported after both a single (Crowell et al., 2010) and multiple gait retraining sessions (Crowell & Davis, 2011). Further, these reductions were maintained one-month post intervention. This evidence suggests gait retraining to be a useful tool in either the prevention of stress injuries or successful rehabilitation post injury. However, to date these studies have largely been confined to treadmill running which does not replicate the training environment of runners. Additionally laboratory time is costly and requires specialist staff.

Accelerometers attached to the skin are routinely used to measure tibial accelerations during running (Laughton, Davis, & Hamill, 2003; Milner, Ferber, Pollard, Hamill, & Davis, 2006). Previous research has found accelerations at the tibia to be overestimated by skin mounted compared to bone mounted sensors reporting differences of up to 2.1 *g* (Lafortune, Henning, & Valiant, 1995). With careful choice of sensor location and attention to application procedures, these errors can be minimised (Pearsall, Henning, & Sterzing, 2002). Due to ethical issues associated with bone mounted accelerometers, skin mounted transducers are routinely used for measuring tibial accelerations in running (Laughton et al., 2003; Milner, Hamill, & Davis, 2007). Tibial shock has been found to differ across speeds (Lafortune, Lake, & Hennig, 1996), with runners often training at a range of run speeds; three speeds were analysed in the present study to reflect this. The wireless inertial sensor used in this study is low cost, commercially available and, with a built in wireless feedback capacity, offers the potential for real-time feedback outside of the laboratory. The aim of this study was to examine the agreement of a wireless sensor with a skin mounted accelerometer in measuring peak axial tibial acceleration during running at a range of speeds to determine its suitability as an ecological valid tool to be used for a gait retraining system.

METHODS: After ethical approval, 13 male participants were recruited for the study (28 ± 5 years; height 1.8 ± 0.1 m; mass 79 ± 9 kg; mean ± SD). All participants provided written informed consent, were rear-foot strikers, running at least 16km per week and free from any lower limb musculoskeletal injury at the time of testing.

An inertial sensor (Scribe Labs, California, USA) containing a tri-axial accelerometer, magnetometer and gyroscope encased in housing (total weight, 9.55g) was used in this study. The inertial sensor was compared against a skin mounted accelerometer which was considered a gold standard and used in previous studies to measure tibial acceleration during running (Barnes, Wheat, & Milner, 2011), with between days reliability measured at 0.87 ($ICC_{2,1}$) (Barnes, 2011). The gold standard sensor used was a uniaxial accelerometer (PCB Piezotronics, Stevenage, UK) attached to a small piece of thermoplastic (total weight, 1.65g); connected to a PCB signal conditioner (model 480E09; gain = 10). Both sensors sampled at 1000Hz.

The gold standard accelerometer was mounted to the inertial sensor using double-sided sticky tape. The sensors were attached to the distal portion of the antero-medial aspect of the tibia, 5 cm above the medial malleolus (Laughton et al., 2003) using double sided sticky tape. This site was chosen due to the relatively thin skin overlying the bone at this point, thus reducing the effect of soft tissue oscillations caused during impact (Hamill et al., 1995). The sensitive axes of the sensors were aligned with each other visually, and to the long axis of the tibia. Tension was applied to the skin at the attachment site to help minimise soft tissue motion (Pearsall et al., 2002), and the sensors were over wrapped tightly with elastic cohesive bandage about the circumference of the shank. To ensure consistency across participants, the same investigator marked the sensor position and applied the sensors on each occasion.

Following a warm up, participants ran at three different speeds in a randomised order categorised as low: 2.5 ms^{-1}, medium: 3.5 ms^{-1}, and high: 4.5 ms^{-1} (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2010). Participants were allowed to rest between trials to ensure they were in no way fatigued. Each run involved the participant running at the target speed for a total of 40 s, with 10 s to regulate running gait and then 30 s to collect data. All trials were completed in a single session and participants wore their own running shoes.

Data were imported into Matlab (Mathworks, R2014a) for analysis. All acceleration data were bandpass filtered between 2 - 75 Hz with a 2nd order Butterworth filter, and then converted to units of *g*. Residual analysis of the data of 10 participants across all three run velocities for both sensors determined the filter choice (Winter, 2009). The sensors were synchronised by way of the participant stamping their foot before starting a run so that the same series of foot strikes were analysed for the data from each sensor. Mean peak positive tibial accelerations, defined as the maximum value during stance, were compared between methods.

To investigate the inertial sensor agreement and accuracy, intraclass correlation coefficient ($ICC_{2,1}$) and 95% limits of agreement (LOA) were used. An ICC value >0.75 was considered good, whilst 0.4 - 0.75 was considered moderate (Fleiss, 1986). Narrower confidence intervals (CI) of the LOA were considered an indication of the accuracy of the inertial sensor. Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL) v21.0., was used for statistical analyses.

RESULTS: 13 male participants were involved in the study however, due to technical difficulties, results from two trials at 4.5 ms^{-1} are not presented. Mean peak tibial acceleration measured by the inertial sensor was higher than the gold standard for all three run speeds, however, the mean differences were small ranging from 0.23 to 0.36 *g* (Table 1), and no significant differences were detected. Means and standard deviations of peak tibial acceleration increased with run speed. The ICC (2,1) indicates the agreement of the inertial sensor with the gold standard accelerometer is good at each run speed: 2.5 ms^{-1} (ICC = 0.92), 3.5 ms^{-1} (ICC = 0.90), 4.5 ms^{-1} (ICC = 0.89). The LOA CI shows a range of 1.20 to 1.57 *g* across running speeds.

Table 1: Summary of results for peak tibial acceleration during running: Inertial sensor compared to gold standard accelerometer.

			ICC			LOA			
Sensor	Run speed (ms^{-1})	Mean acceleration ± SD (*g*)	Single measure	Lower bound	Upper bound	Mean difference (*g*)	95% CI	Lower CI	Upper CI
Gold standard Inertial	2.5	4.04 ± 1.55 4.28 ± 1.57	0.92	0.76	0.97	0.24	1.20	-0.96	1.44
Gold standard Inertial	3.5	5.92 ±1.83 6.15 ± 1.92	0.90	0.71	0.97	0.23	1.65	-1.42	1.88
Gold standard Inertial	4.5	7.88 ± 1.87 8.24 ± 1.73	0.89	0.66	0.97	0.36	1.57	-1.21	1.94

DISCUSSION: The aim of this study was to examine the agreement of the inertial sensor and a gold standard accelerometer in measuring peak vertical tibial acceleration during running, to determine its suitability as a wearable sensor for use in real-time feedback within gait retraining.

ICC results at all three run speeds show excellent agreement of the inertial sensor with the gold standard accelerometer. Across run speeds the mean differences are low and the CI is less than 1.7 g. With previous research reporting up to 50% reductions in peak tibial acceleration following real-time feedback interventions (Crowell & Davis, 2011; Crowell et al., 2010), these values would indicate that the inertial sensor is capable of detecting intervention related changes in peak tibial acceleration. Further, the results support the use of the sensor as an ecologically valid tool for real-time feedback in gait retraining. Previous research has demonstrated other kinetic and kinematic variables are also reduced through reduction of tibial acceleration values at impact and these have been associated with a reduced injury potential (Clansey, Hanlon, Wallace, Nevill, & Lake, 2013). The inertial sensor has the possibility of measuring other variables to monitor these changes. The mean peak tibial acceleration values are similar to those in previous research (Barnes et al., 2011; Laughton et al., 2003). The means and standard deviations of the peak tibial acceleration increased with run speed, which has been found in previous research (Lafortune, et al., 1996).

This study had some limitations, which should be considered when interpreting the results. Although the sensors were manually aligned, minor misalignment of the axes of both sensors may have caused cross talk between axes of the inertial sensor, and could affect the sensor's vibration exposure (Decker, Prasad, & Kawchuk, 2011). As the gold standard accelerometer was mounted onto the inertial sensor, and taking into account the difference in mass between devices, this could have contributed to resonance in the uni-axial accelerometer data. Tibial acceleration can be affected by variables such as running kinematics, running surface and footwear (Hennig & Lafortune, 1991). To minimise this effect all participants were heel strikers and ran on the same treadmill, however footwear was not controlled for.

CONCLUSION: The results of this study suggest that the inertial sensor is a suitable tool for measuring tibial shock running at a range of speeds. Therefore the sensors represent a suitable tool for providing real time feedback to runners in the field. Real-time feedback of peak tibial shock during running using a sensor such as the inertial sensor will aid sports scientists and coaches to monitor and reduce peak tibial shock experienced by runners. The inertial sensor is easy to use, wireless, and waterproof meaning it could extend the laboratory sessions of gait analysis into real world situations of running. Further research should seek to integrate this sensor into real-time feedback systems to be worn by runners in the field.

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Acknowledgment

We would like to thank Tim Clark and John Litschert at Scribe Labs for providing the inertial sensor, and for their invaluable technical help and assistance.