IMPACT LOAD MONITORING USING INERTIAL MEASUREMEMENT UNITS ON DIFFERENT VISCOELASTIC SPORT SURFACES: A TECHNICAL REPORT

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Inertial measurement units (IMU) provide the opportunity to measure and monitor loads during gymnastics training on a variety of viscoelastic surfaces. Previously these loads have been estimated from force platform (FP) testing of discrete skills such as somersault landings. This study examined the relationship between peak impact loads measured with an IMU and a FP. A 9 kg slam ball with a fixed IMU was dropped from various heights (40, 60, 80 cm) and surfaces (no mat, rubber, 3-10 cm deep gymnastics mats). There was a significant difference between the two measures for all conditions (p=0.028), except for the 40 cm drop onto the rigid force platform surface. IMUs enable the true load on the gymnast to be measured when completing skills on less rigid, viscoelastic surfaces, which may be lower or higher than what has been previously estimated using force platforms.

KEY WORDS: force plate, ground reaction force, acceleration, IMU, gymnastics.

INTRODUCTION: Energy transfer to and from a viscoelastic surface can have a large influence on an athletes performance and safety (Stefanyshyn & Nigg, 2003, p31). Many of the surfaces encountered in gymnastics are viscoelastic and compliant. These compliant surfaces have less stiffness and will generally enable greater deformation, energy storage, and energy return (Stefanyshyn & Nigg, 2003, p32). The energy return enables gymnasts to project themselves higher in order to perform leap, jump, and acrobatic manoeuvres. Gymnastics movements such as a double stretched (layout) somersault on the sprung floor would not be physically possible on less compliant and stiffer surfaces such as hard courts with acrylic layers (e.g. Plexipave).

The nature of the interaction between a surface and an athlete has been associated with injury risk. That is because if the loads are too large the internal structures may become damaged (Butler, Crowell and Davis, 2003; Mills, Pain, Yeadon, 2006). On a more compliant, low stiffness surface the athlete needs to interact using higher total musculoskeletal (vertical) stiffness in order to maximise energy input and return during sequential impact movements. In gymnastics this type of surface interaction is characteristic of floor tumbling. However when a gymnast lands after a vault onto safety matting, the area deformation of the surface facilitates force dissipation (Pain, Mills, Yeadon, 2005), and the gymnast must land with enough stiffness in order to maintain balance. The biomechanics of the athlete interaction with hard court and gymnasium floor is dissimilar due to the less compliant, higher stiffness surfaces. On a hard court, for example, if the same tasks could be physically be performed (not possible due to less energy return), the musculoskeletal stiffness would need to be lower due to the lower compliance surface.

Musculoskeletal stiffness is, in simple terms, a measure of the peak force with respect to the amount of body deformation that occurs from flexion of the joints during surface impact (Butler et al., 2006). Therefore when greater musculoskeletal stiffness is required to perform a skill or task the athlete is typically experiencing higher external and internal loads. Measuring the internal loads such as joint reaction forces and moments has required expensive and complex tools that are predominantly laboratory-based and require highly trained staff and time-intensive analyses (Settuain Millor, Gonzelez-Izal, Gorostiaga, Gomez, Alfaro-Adrian, Maffiuletti, Izquierdo, 2015). Futher, it has restricted sports movement assessment to a predefined space due to the requirement to land onto a force platform (Settuain et al., 2015).The influence of biomechanics on gymnastics training to date has therefore been limited. Technological advances in sensor technology such as wireless accelerometers and inertial measurement units (IMU) provides a new alternative tool for biomechanical testing. This technology has fuelled biomechanical testing of athletes in a variety of applied contexts (e.g. tibial loads during running; Sheerin, Besier, Reid, Hume, 2016). Accelerometers and IMU systems provide linear acceleration values in a sensor-fixed Cartesian reference frame (X,Y,Z; Settuain et al., 2015). IMUs also provide information on orientation and angular displacement.

IMU technology now provides, for the first time, the opportunity to objectively monitor a gymnast's internal impact loads during training. However the position of the IMU on the body will affect estimates of internal impact loading (Simons & Bradshaw, 2016). The most common position of accelerometers for measuring internal impact loads have previously been the upper back (Wundersitz, Gastin, Richter, Robertson, & Netto, 2014), lower back (Howard, Healy, Conway, & Harrison 2014), and the tibia (Raper et al., 2014); and all of these studies have examined movement tasks on less compliant and stiffer surfaces. Secondly, whilst moderate to strong relationships have been found between these measures and the external ground reaction force (Simons & Bradshaw, 2016), this is unlikely for more compliant surfaces. In fact, it has recently been revealed that for gymnastics surfaces, an IMU placed on the lower back may provide a better indication of the landing load experienced by the gymnast than the more traditional measure of an external ground reaction force (Bradshaw, Grech, Joseph, Calton, Hume, 2016). Therefore, the purpose of this technical study was to examine the relationship between peak impact loads measured with a force platform (Peak Resultant Force) and an IMU (Peak Resultant Acceleration) on a variety of viscoelastic sport surfaces.

METHODS: ***Procedure and Data Collection*** A 9.07 kg slam ball (SPRI Products, West Chester, OH, U.S.A), with an inertial measurement unit (IMU; Blue Thunder Sensor, iMeasureU, Auckland, N.Z.) fixed on the top using athletic tape, was dropped from three heights (40, 60, 80 cm) onto one portable, multicomponent force platform (9286A, Kistler, Winterhur, Switzerland). A slam ball was specifically used, instead of a medicine ball, as it was thought to better represent the human body with its load dampening system during ground impacts. The drop tests were then repeated for the 60 cm height onto six different surface conditions (0.5 cm deep rubber gymnasium floor [Everlast, Regupol, Minto, NSW, Australia], 3 cm deep carpeted gymnastics foam mat, 6 cm deep carpeted gymnastics foam mat, 9 cm deep carpeted gymnastics foam mat [A8-233, Acromat, Mile End South, SA, Australia], 4 cm deep vinyl gymnastics foam mat [A8-410, Acromat], 10 cm canvas gymnastics foam landing mat [A8-245, Acromat]). Six drop tests were completed for all conditions. The IMU and force platform data were both sampled at 500Hz. The force platform data was captured onto a personal computer using the manufacturer's software (Bioware, version 5.3.2.9, Kistler, Winterhur, Switzerland). The IMU data was captured separately using an iPhone (iPhone8, Apple Inc., Cupertino, California, U.S.A.) via a Bluetooth connection and the manufacturer's research application (app) software (IMU Research, version 3.2). The two data collection systems were not time synchronised.

Data Analyses The peak resultant ground reaction force was identified and normalised with reference to the slam ball weight (88.98 N) for each drop trial. The acceleration data were exported from the iPhone via email onto a personal computer. The raw accelerations in the x, y and z directions were then combined into a resultant acceleration using the following equation: $a_r = \sqrt{a_x^2 + a_y^2 + a_z^2}$ where a_r is the resultant acceleration, a_x is the acceleration in the x-direction, a_y is the acceleration in the y-direction, and a_z is the acceleration in the z-direction. All accelerations were expressed in gravitational units (g) (one gravitational unit is equal to the gravitational acceleration of -9.81 m/s^2). The peak resultant acceleration (PRA) was then identified for each drop trial. The data was collated in a spreadsheet (Excel) and then imported into SPSS Statistics software (version 22, IBM, Armonk, NY, U.S.A.). An alpha level of 0.05 was set for all statistical analyses. Normality of the data set was determined using a Shapiro-Wilk test. The data was not normally distributed and therefore non parametric statistics were subsequently employed. A Wilcoxon signed ranks test was used to identify if there was a difference between the two measures (acceleration, force). Spearman correlations were used to identify relationships between the two measures (acceleration, force).

RESULTS: The peak resultant ground reaction force and acceleration measures for each drop height and sports surface are displayed in Figures 1 and 2. No relationship was identified between any of the force and acceleration measures. In fact, the force and acceleration results were statistically different for all test conditions (Z=-0.314, p=0.028) with the exception of the 40 cm drop test on the rigid force platform surface (Trial 1 illustrated in Figure 3).

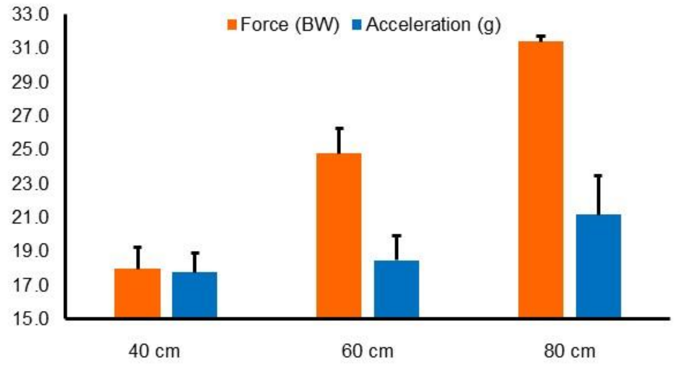

Figure 1: Peak resultant acceleration and ground reaction force for the standard force platform surface testing from three drop heights. Abbreviations: BW is the normalised peak resultant impact force with respect to Body Weights, and g is the normalised peak resultant acceleration with respect to the gravitational constant of -9.81 m/s^2.

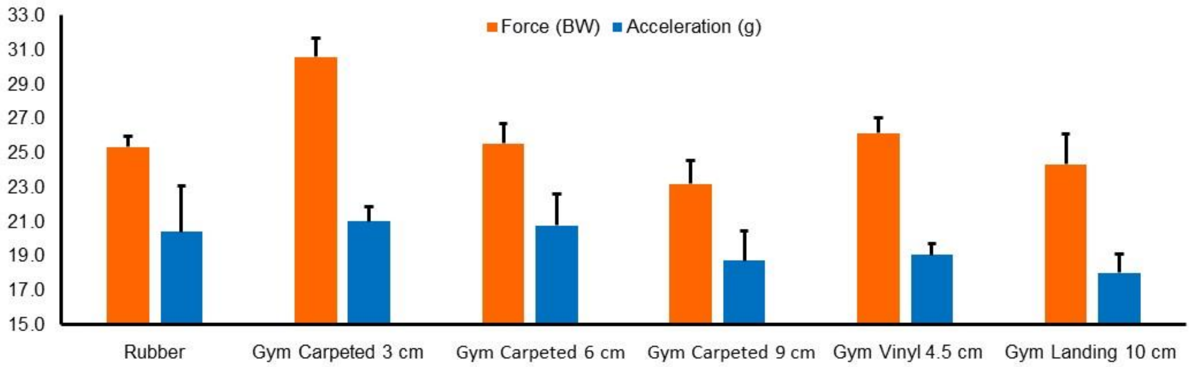

Figure 2: Peak resultant acceleration and ground reaction force for the 60 cm drop height and the viscoelastic sport surfaces.

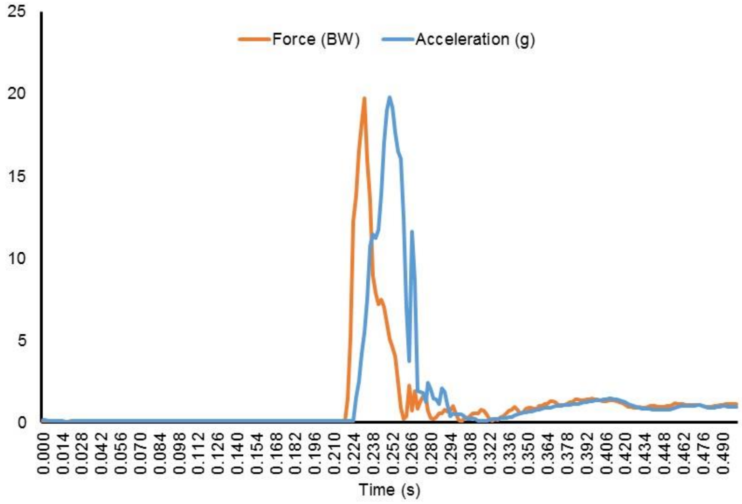

Figure 3: Example force and acceleration-time curves from the force platform and IMU measuring tools. Note that the two measuring tools were not time synchronised.

DISCUSSION: This technical study identified no relationship between impact loads when measured using a force platform and an IMU. This reveals that for ground impacts on viscoelastic surfaces, regardless of stiffness and compliance, the two measures are different and therefore require separate interpretation. In this case the force platform provides a traditional measure of the external load from the peak ground reaction force recorded underneath the surface/matting. Whereas the IMU provides an estimate of the internal load experienced at that joint (e.g. lower back), taking into account the natural dampening system of the human body (musculoskeletal, biomechanical pattern), and the dampening system of the viscoelastic surface (Pain et al., 2005), which will often act to decrease the impact load. This is consistent with previous studies of running, where it has been stated that vertical ground reaction forces are not the most appropriate method for evaluating impact load (Hamill, Boyer, Weir, 2018). The only condition where the two measures were statistically similar were on the aluminium force platform surface for the lower drop height (40 cm). For all other conditions, the peak ground reaction forces were much larger than the peak accelerations. This study also demonstrates the effect of surface on the external loads and estimates of internal loads. The impact force and acceleration was highest on the 3 cm gymnastics floor surface, and lower for the same, but thicker (9 cm) surface. Overall, the peak acceleration was lowest on the 10 cm canvas landing mat, demonstrating that this type of mat is effective at dissipating forces. This technical study used a slam ball and therefore whilst it has provided some technical insights on using these biomechanical tools to measure impact loads, the results should be treated with caution when applied to human performance. Further only one slam ball mass was tested, which was well below (9.02 kg) the typical mass of a gymnast. Further study that incorporates higher ball masses, higher drop heights (e.g. 1m), a higher sampling frequency (1000Hz), and human trials is recommended.

CONCLUSION: Gymnastics involves the performance of multiple movements on a wide range of viscoelastic surfaces. IMUs enable the overall internal load on the gymnast to be estimated when completing these movements. These peak acceleration measures may be lower or higher than what has been previously estimated using force platforms, depending on the specific surface that they are interacting with, the movement being performed, and the gymnast's strength and technique.

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