# Kinetic and kinematic analysis of stamping impacts during simulated rucking in rugby union

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**Kinetic and kinematic analysis of stamping impacts during simulated rucking in rugby union**

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**Abstract**

Laceration injuries account for up to 23% of injuries in rugby union. They are frequently caused by studded footwear as a result of a player stamping onto another player during the ruck. Little is known about the kinetics and kinematics of rugby stamping impacts; current test methods assessing laceration injury risk of stud designs therefore lack informed test parameters. In this study, twelve participants stamped on an anthropomorphic test device in a one-on-one simulated ruck setting. Velocity and inclination angle of the foot prior to impact was determined from high-speed video footage. Total stamping force and individual stud force were measured using pressure sensors. Mean foot inbound velocity was 4.3 m · $s^{-1}$ (range 2.1 - 6.3 m · $s^{-1}$). Mean peak total force was 1246 N and mean peak stud force was 214 N. The total mean effective mass during stamping was 6.6 kg (range: 1.6 - 13.5 kg) and stud effective mass was 1.2 kg (range: 0.5 - 2.9 kg). These results provide representative test parameters for mechanical test devices designed to assess laceration injury risk of studded footwear for rugby union.

**Keywords:** 3D analysis, Impact, Injury & prevention, Footwear, Kinetics

## Introduction

Rugby union is a field sport in which studded footwear is worn to increase traction on the pitch. Rugby union is a full-contact sport with an injury prevalence of approximately 69 injuries per 1000 hours of match play at the professional level; lacerations account for up to 23% of these injuries (Bathgate, Best, Craig, & Jamieson, 2002). Laceration injuries sustained by players can be severe, frequently requiring stitching and exposing players to risks of infections (Gibbs, 1993; van den Eijnde, Peppelman, Lamers, van de Kerkhof, & van Erp, 2014). Studded footwear is often highlighted in the media as the cause of laceration injuries occurring in field sports (Ferrie, 2001; Morgan, 2015). The problem was also emphasized by Hall & Riou (2004) who cited three case studies of severe laceration injuries and suggested that the design of the stud was the causal factor.

To mitigate the risk of laceration injuries in rugby union, stud design is regulated by its international governing body, World Rugby. The testing protocol for studs as described in World Rugby Regulation 12 (World Rugby, 2015) and the British Standards (BS 6366:2011), is currently recommended to manufacturers of studded footwear. Both standards describe two 'performance tests' for assessing laceration injury risk of a stud design. Test A ('skin glancing or raking') uses a pendulum to impact and ‘glance’ a stud over a skin and soft tissue simulant. No guidelines are provided for inbound velocity or impact energy. Test B ('skin stamping') involves a stud attached to an 8.5 kg mass which is dropped (50 mm) onto a skin and soft tissue simulant. The skin and soft tissue simulant materials used in Regulation 12 are not prescribed; suggestions are given to use a poromeric shoe upper material in combination with gelatine. The recommended drop test parameters in test B will produce an impact energy of 4.2 J. There is currently no supporting evidence for the selection of the test parameters used in these standards. It is unknown if the current test protocol replicates the kinetics and kinematics of stud-player impacts in the field.

Stamping in the ruck has been identified as the playing scenario most frequently causing laceration resulting from stud-player impacts in rugby union (Oudshoorn, Driscoll, Dunn, & James, 2016a). Stamping in the ruck is a purposeful movement where the player brings their foot heavily down on another player who is lying on the ground. Although illegal, stamping is still common in rugby play. The selection of test parameters for a mechanical test device to assess laceration injury risk of stud design should replicate the playing scenario responsible for laceration injuries in the field. Kinetic and kinematics of rugby stamping impacts are currently unknown.

When replicating stud-player impacts in a mechanical test device, the magnitude and direction of the inbound velocity of the stud, its inclination angle and the effective mass of the impact need to be considered. There is no direct way to measure the effective mass of an impact; however, a variety of approaches can be used to calculate it from kinetic and kinematic measurements (Lenetsky, Nates, Brughelli, & Harris, 2015). Neto et al. (2012) calculated effective mass using the integral of force (N) with respect to time and divided by the change in velocity on impact, showing a need for obtaining both kinetic and kinematic data from stud-player impacts in order to estimate effective mass.

The availability of lightweight and flexible force sensors (Tekscan Inc, Boston, USA) have recently become more prevalent and they have proven useful for measuring in-vivo impact forces of basketball and rugby players (Halkon, Mitchell, Payne, & Carbo, 2014; Halkon, Webster, Mitchell, & Mientjes, 2012; Pain, Tsui, &

Cove, 2008). The flexible nature of the sensors ensures the safety of the player during impact. A further advantage of this type of sensors over the use of force plates or load cells is the ability to obtain the spatial distribution profile of the force.

Measurement of kinematics in participant based research where the absolute motion is of interest can be undertaken with optical, electromagnetic, ultrasonic or inertial systems (Kirtley, 2006). Optical systems can provide high accuracy combined with minimal interference to the participant.  Thus, a combination of pressure sensing and camera-based systems allow for in-vivo kinetic and kinematic measurements of player impacts in sport (Preatoni et al., 2012).

The purpose of this study was to measure the inbound velocity, stud angle and impact force associated with rugby stamping impacts. The effective mass and impact energy of the stamps were derived from these measurements. A combination of measurement systems were used to obtain kinetic and kinematic information of stamping impacts, whilst maintaining a representative rucking situation for participants. The outcomes of this study can be used to inform test parameters of new mechanical tests that aim to replicate stud-skin contacts in rugby.

## Methods

### *Participants*

With institutional ethical approval, twelve male participants (mean ± SD: age: 27.7 ± 4.2 years, height: 176.5 ± 5.8 cm and weight: 76.3 ± 7.6 kg) gave informed consent to participate in this study. All participants were recreationally active. Ten out of twelve participants had previous experience of playing rugby, although none were currently engaged in the sport. Participants were asked to set up a one-on-one ruck and perform a stamping motion onto the chest of an anthropomorphic test device (ATD) used as a surrogate player (Figure 1). Each pair of participants was shown an instructional video to help standardise the movements performed. Participants performed test trials until they felt comfortable with their rucking partner and the movements. Participants were asked to perform 10 stamping trials each. A trial was successful if the participant pushed their partner away from the ATD ('rucked over') and stamped on the ATD's chest without losing balance.

**** Figure 1 around here ****

*Equipment*

Participants wore a pair of rugby shoes (Kipsta Density 300, Decathlon, size 8.5-10.5 UK), which had an 8-stud configuration of aluminium rounded studs (10 mm diameter and minimum stud spacing of 32 mm). Three high contrast circular markers were placed on each shoe; at the heel cup at level with the lateral malleolus, at the lateral front stud and at the lateral rear stud. The ATD was a Hybrid III 50$^{th}$ percentile man (Humanetics Innovative Solutions, Plymouth, USA). The Hybrid III ATD is commonly used in compliance and regulatory testing as well as research and can generally be regarded as a widely accepted human substitute (Crandall et al., 2011).

Two gen-lock synchronised high-speed cameras (Phantom Miro Lab 320, Vision Research, Wayne, USA) were positioned 3 m away from the ATD at an angle of 60°

to each other (Figure 2). Each impact was filmed at 1000 frames per second for 1.5 s at a resolution of 1280 x 800 pixels. A three-dimensional motion capture volume, measuring 1 x 1 x 1 m was calibrated (Check3D). The global coordinate system was defined with the z-axis corresponding to the true vertical. Accuracy of the manual identification of shoe markers was ± 0.13 mm.

Two pressure sensors (Tekscan, F-scan, 3000E 'Sport') sampling at 750 Hz, were used to measure exerted pressure of each shoe - ATD impact. Each sensor had 956 pressure sensing elements with a spatial resolution of 25 $mm^2$. Two sensors were placed on the chest of the ATD in such a way that maximised their surface area and minimised the overlap between sensors (Figure 2). The chest was used because of its relatively large surface area, making full use of the sensors' size

**** Figure 2 around here ****

*Analysis*

For each valid trial, marker position data were manually identified for 10 frames prior to first impact. The mean marker velocity 10 ms prior to first impact was defined as the inbound velocity of the foot. The orientation angles of the shoe were calculated following a modified approach of the method by Driscoll et al. (2015). For this method, the relative position of each marker and stud is required. A static reference position for each shoe was obtained by a 3D laser scanner (CIMCORE Arm 5024, EuroPac 3D, Crewe, United Kingdom). This scan was also used to define a local coordinate system for the shoe. A direction cosine matrix (order ZXY) was used to transform the local coordinate system to the global and derive three Euler angles (pitch, yaw and roll). A positive pitch angle refers to the foot angling a toe-down prior to impact (rotation about the x-axis); a positive roll angle corresponds to an eversion of the foot (rotation about the y-axis). The yaw angle was not used in this study. Estimated error following this method is ± 0.5 mm (Driscoll et al. 2015).

A trial was included for total force analysis if the participant managed to completely contact the pressure sensors during the stamp, i.e. no stud contact outside the pressure sensors was made. For individual stud force analysis, partial contact with the pressure sensors sufficed. Pressure sensors were calibrated to output force using the calibration method described by Oudshoorn et al. (2016b), which incorporates a spherical impactor and uses silicone to match the estimated loading rate of the impact. Calibrated stamping impact data were loaded into MATLAB® (R2015a, the Mathworks Inc, Massachusetts, United States). Peak total force was calculated from the summation of all activated pressure elements and defined as the time-frame with highest summed force. A custom written script was used to calculate peak stud force. Preliminary analysis of pressure sensor data showed that the number of sensing elements activated by one stud during an impact was dependent on the impact force of the stud, with higher forces activating a larger number of elements. Data of the pair of sensors was combined into one grid and three elements with the highest pressure values were identified as the starting points. A grid of 5 x 5 elements around a peak was identified as a stud impact. Thereafter, because of the growing nature of the impact, a 'pass or fail' criterion was put in place for consecutive elements. An element 'passed' and was included in the stud force when it had a lower or similar force (≠ 0 N) than one of its neighbouring elements which were closer to the starting element. An element 'failed' when it had a higher force than all of its neighbouring elements; it was assumed that the element was part of a different stud impact. This process is visualised in Figure 3. If an element passed, the software then looked at its neighbouring elements and see if they should pass as well. A maximum of five elements in each direction from the starting point could have been included in a single stud impact, corresponding to 25 mm distance. The closest distance between two studs in the shoes used for this research was 32 mm. The process of defining stud impacts was repeated for the three highest pressure values in each time frame. Peak stud force was defined as the highest single stud force at one time-frame.

**** Figure 3 near here ****

A trial was included for effective mass and impact energy calculations if that trial met the inclusion criteria for both kinematic and force analysis. To obtain the effective mass of hand striking impacts in combat sports, Neto et al. (2012) defined effective mass through Equation (1);

**** Equation 1 around here ****

With $m_e$ being effective mass of the impact, *Fdt* being force as a function of time with *dt* representing infinitesimal increment of time, $t_1$ the time of first impact, $t_2$ the time that the hand stops momentarily during collision and $\Delta v$ the change in velocity of the striking object during this time. For this study, the effective mass of the total stamping force and the stud force was calculated using equation (1) and the values of $t_1$ and $t_2$ were obtained from visual inspection of the high-speed videos. Peak stamping force coincided with a velocity value of approximately zero ($t_2$). The impact energy ($E_{kin}$) of the total stamp and for a single stud was calculated by using Equation (2).

**** Equation 2 near here ****

Where change in velocity ($\Delta v$) is equal to the inbound velocity; assuming that at maximum displacement the foot becomes momentarily stationary and all energy is dissipated. No filter was applied to the data in order to conserve original peak values.

**Results**

A total of 110 trials, performed by 12 participants, were included in this study. Kinematic data were obtained from eight of these participants, resulting in 75 trials with velocity and inclination angle data on the stamping impacts (Table 1).

**** Table 1 near here ****

The range of resultant inbound velocities of the foot during these stamps was 2.1 to 6.3 $m \cdot s^{-1}$. The mean resultant inbound velocity was 4.3 $m \cdot s^{-1}$. Inbound velocity of the foot during rugby stamping impacts consisted of a horizontal and vertical component, and they were of a similar magnitude (mean velocity 3.0 and 2.8 $m \cdot s^{-1}$, respectively). The angle of the foot prior to impact ranged from +35° (toe down) to -13° (heel strike); within this variation, roll angles varied from -31 to 23° (Figure 4).

**** Figure 4 near here ****

All trials made contact with the sensor; of these, 15 trials partly missed the sensor. Therefore peak stud force was calculated over 110 trials and peak total force over 95 trials. Peak total force measured during the stamping impacts ranged from 482 to 2670 N; peak stud force ranged from 93 N to 370 N (Table 2). Effective mass and impact energy were calculated using force and velocity data. Following the inclusion criteria for force and velocity data, the stud effective mass and stud impact energy was determined from 75 trials and total effective mass and total impact energy from 67 trials. The total effective mass ranged from 1.6 to 13.5 kg and total impact energy ranged from 15 to 122 J (Table 2).

**** Table 2 near here *****

## Discussion

Stamping in the ruck in rugby union has been thought to cause laceration injuries (Oudshoorn et al., 2016a), but limited kinetic and kinematic information on stud-skin interactions is available in literature. Kinetic and kinematic information of such impacts can be used to inform mechanical test methods assessing laceration injury risk of stud designs. Previous studies aiming to replicate slide tackling in football have estimated the effective mass of the foot at 0.1 kg (Ankrah & Mills, 2003) and 4.6 kg (Payne, Mitchell, & Bibb, 2013), the latter assuming that the mass was equal to part of the foot and leg of the player. The large difference between these effective masses reiterates the need for validation of such impact kinetics by biomechanical studies. Quantifying the force required to lacerate human skin is considered complex due to the large number of influencing variables, e.g. sharpness and material of the impacting object, and inbound velocity (Parmar, Hainsworth, & Rutty, 2012). Test methods for assessing laceration injury risk should therefore focus initially on replicating inbound velocity, attack angles and impact mass of injury events.

Current studded footwear standards (BS 6366:2011 and Regulation 12, World Rugby, 2015) stipulate an inbound velocity of $\sim 1\ \mathrm{m \cdot s^{-1}}$ (50 mm free fall) and an 8.5 kg drop mass. In this study, 12 male participants each performed 10 stamps on an ATD during a ruck-type setting. The mean resultant inbound velocity measured was $4.3\ \mathrm{m \cdot s^{-1}}$, which is higher than the $1.0\ \mathrm{m \cdot s^{-1}}$ prescribed in the current studded footwear standards. Mean effective mass per stud was measured to be lower than the current standards (1.2 versus 8.5 kg, respectively). However, mean stud impact energy was higher in this experiment than in the current standards (9.5 versus 4.2 J, respectively). This was due to the higher inbound velocities measured compared to those prescribed by the studded footwear standards. It can be concluded that current studded footwear standards overestimate the effective mass per stud but underestimate the inbound velocity and impact energy for stud-skin interactions during stamping. This has significant implications for the validity of the current standard and suggests that the development of a new task representative mechanical test device is necessary.

This study aimed to quantify impact parameters associated with amateur rugby players; consequently the recruitment criteria for participants did not include minimum playing experience in rugby union. Stamping in the ruck is an illegal action in rugby union and the type of foot movement is unlikely to require a specific skill level from the participants. The body weight of the participants (76 ± 7.6 kg) was low in comparison to professional male rugby players (100 ± 12.1 kg; Brooks, Fuller, Kemp, & Reddin, 2005). However, the study aimed to quantify impact parameters associated with amateur rugby players, and body mass was similar to British club level players (77.6 ± 10.6 kg; Nicholas, 1997). Further, the mean stud impact energy generated by participants was twice as high as recommended in the current standard (9.5 J versus 4.2 J, respectively). In this study, the chest area of a Hybrid III ATD was used. The chest stiffness of the Hybrid III ATD has previously been found 10% stiffer than the chest stiffness of human volunteers (Backaitis & St-Laurent, 1986), which could have led to an increase in peak stamping force in this study. Nevertheless, the use of a Hybrid III ATD as a surrogate player was necessary for both safety and ethical reasons. It is currently unknown what area of the body is most commonly affected by stud laceration injuries. Using a different area of the body could have influenced the results of this study.

This study identified kinetic and kinematic impact parameters of a stamping impact to inform studded footwear standards. It was found that the current standards do not represent the observed impact parameters. Future work should focus on translating the observed range of impact parameters into a new realistic design for a mechanical test device. Furthermore, other sports which use studded footwear, such as association and American football, can have different stud-skin impact kinetics and kinematics. To develop a general test method that is applicable to a range of studded footwear sports, the mechanics of the respective stud laceration injury scenarios also need to be identified.

## Conclusion

Mechanics of stud-player impacts in field sports, in particular stamping during the ruck in rugby, were previously unknown. This information is important when designing mechanical test devices for assessing the laceration injury risk of studded footwear; the test parameters of such devices should aim to replicate game-relevant kinetics and kinematics. When stamping on a surrogate player in a laboratory setting, mean inbound foot velocity of the stud impact was 4.3 $m \cdot s^{-1}$. Both heel striking and toe-down impacts were observed. Mean peak stamping force was 1246 N and the mean peak stud force 214 N. Consequently, the mean effective mass of stud impacts was 6.5 kg, which equates to 1.2 kg per stud. The findings of this study show that current studded footwear standards do not replicate impact parameters of stamping impacts in ruck-type settings; current standards underestimate inbound velocity and impact energy and overestimate stud mass. Furthermore, no inbound velocity angle or foot angle is incorporated in the current standards. The development of a future mechanical test device for assessing laceration injury risk of studded footwear should replicate impacts kinetics and kinematics described in this study.

## Disclosure statement

The authors declare no potential conflict of interest

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**Equations**

Equation 1:

$$m_e = \frac{\int_{t1}^{t2} F dt}{\Delta v} \tag{1}$$

Equation 2:

$$E_{kin} = \frac{1}{2} m_e \Delta v^2 \tag{2}$$

**Tables**

Table 1: Pre-impact kinematics of stamping in the ruck (N = 75).

| | Horizontal foot velocity ($m \cdot s^{-1}$) | Vertical foot velocity ($m \cdot s^{-1}$) | Resultant foot velocity ($m \cdot s^{-1}$) | Foot pitch angle (°) | Foot roll angle (°) |
|---|---|---|---|---|---|
| Mean | 3.0 | 2.8 | 4.3 | 10.3 | -5.2 |
| Range | 0.1 - 5.7 | 1.1 - 4.5 | 2.1 - 6.3 | -13.2 - 35.4 | -31.0 - 23.3 |

Table 2: Impact kinetics of stamping in the ruck

| | Peak total force (N) | Total effective mass (kg) | Total impact energy (J) | Peak stud force (N) | Stud effective mass (kg) | Stud impact energy (J) |
|---|---|---|---|---|---|---|
| Mean | 1245.5 | 6.5 | 56.9 | 214.0 | 1.2 | 9.5 |
| Range | 482.3 - 2670.2 | 1.6 - 13.5 | 15.1 - 122.4 | 93.3 - 369.9 | 0.5 - 2.9 | 1.5 - 18.7 |
| No. of trials | 95 | 67 | 67 | 110 | 75 | 75 |

**Figure captions**

Figure 1: Two participants in a one-on-one rucking formation with the participant on the right stamping on the ATD.

Figure 2: Schematic representation of test set-up. The pressure sensors were placed as to minimise overlap and maximise surface area.

Figure 3(a): Process of defining a stud impact with a central starting point (black), elements included in stud impact (grey) and search grid (white); (b) Example of a grid with three stud impacts.

Figure 4: Range of boot orientation angles found for pitch (left) and roll (right).