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SPECIFIC TACKLING SITUATIONS AFFECT THE BIOMECHANICAL DEMANDS EXPERIENCED BY RUGBY UNION PLAYERS

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Headings: Biomechanics of Rugby Tackling

Abstract:

Tackling in Rugby Union is an open skill which can involve high-speed collisions and is the match event associated with the greatest proportion of injuries. This study aimed to analyse the biomechanics of rugby tackling under three conditions: from a stationary position, with dominant and non-dominant shoulder, and moving forward, with dominant shoulder. A specially devised contact simulator, a 50 kg punch bag instrumented with pressure sensors, was translated towards the tackler (n=15) to evaluate the effect of laterality and tackling approach on the external loads absorbed by the tackler, on head and trunk motion, and on trunk muscle activities. Peak impact force was substantially higher in the stationary dominant (2.84 ± 0.74 kN) than in the stationary non-dominant condition (2.44 ± 0.64 kN), but lower than in the moving condition (3.40 ± 0.86 kN). Muscle activation started on average 300 ms before impact, with higher activation for impact-side trapezius and non-impact side erector spinae and gluteus maximus muscles. Players' technique for non-dominant side tackles was less compliant with current coaching recommendations in terms of cervical motion (more neck flexion and lateral bending in the stationary non-dominant condition) and players could benefit from specific coaching focus on non-dominant side tackles.

World count: 200

Keywords: EMG, tackling, impact forces, kinematics, muscle activation

Introduction

Rugby Union (rugby) is a team sport that involves collisions between players, and is associated with high injury incidence (Williams, Trewartha, Kemp, & Stokes, 2013). The most recent evidence from the 2014-15 season of the English Premiership Rugby Injury Surveillance Project (englandrugby.com) confirms that the tackle is the match event associated with the greatest proportion of injuries (36% of 645 injuries), and that the most common injury diagnoses for tacklers are concussion, quadriceps haematoma, cervical stinger/burner, and brachial plexus stinger/burner. Three out of four of the most common injury types for tacklers involve upper body regions. Rugby participation has also been associated with chronic degeneration of cervical spine structures (Berge, Marque, Vital, Senegas, & Caille, 1999; Castinel et al., 2010) and impaired cervical function (Pinsault, Anxionnaz, & Vuillerme, 2010), both for forwards and backs players. Although the incidence of permanent disability injuries related to rugby activities falls within the 'tolerable risk' category (Fuller, 2008; Kuster, Gibson, Abboud, & Drew, 2012), severe upper spine injuries may happen on rare occasions, with approximately 40% of these catastrophic injuries being attributed each to the tackle and scrum events (Brown et al., 2013; Quarrie & Hopkins, 2008). Moreover, shoulder dislocation/instability diagnoses are amongst the highest risk (days absence per unit time) of all injuries for both backs and forwards (Brooks, Fuller, Kemp, & Reddin, 2005), and taken together the epidemiological evidence confirms that injuries to the head/neck/shoulder region of tacklers are a player welfare concern.

The rugby tackle is an open and unpredictable event in which the tackler engages with the ball carrier normally in an attempt to bring the ball carrier to the ground (McIntosh, Savage, McCrory, Frechede, & Wolfe, 2010; Quarrie & Hopkins, 2008). Given the many possible combinations of movements performed by the ball carrier-tackler dyad, the biomechanics of the tackle is a very difficult situation to reproduce experimentally and to assess through reliable and ecologically valid measurements. Currently, there is lack of information about forces, muscle activations, motions and stresses on anatomical structures caused by specific rugby contact events like tackles, and the limited understanding of specific anatomical loading patterns and injury mechanisms has arguably hindered the deployment of effective injury prevention interventions in relation to the tackle.

Milburn (1995) applied Newton's second law of motion to empirical data to estimate the load experienced by a player while tackling or being tackled. Inferred forces were higher than 5 kN and would have exceeded the injury thresholds suggested for both shoulder (Duprey, Bruyere, & Verriest, 2007) and cervical spine (Burstein, Otis, & Torg, 1982; Przybyla, Skrzypiec, Pollintine, Dolan, & Adams, 2007) structures. Pain, Tsui, & Cove, (2008) estimated contact forces between 1.00 and 1.53 BW by applying thin-film pressure sensors on the tackler's shoulder during simulated tackle impacts. Higher magnitudes (1.95 - 2.31 BW), were found when larger sensors positioned on a punch bag simulating the ball carrier were used (Usman, McIntosh, & Frechede, 2011). Therefore, it appears that the forces exchanged between tackler and ball carrier are much lower when measured directly from pressure sensors than in the indirect estimation using rigid body mechanics assumptions. Arguably, the most recent studies did not include the movement of the ball carrier in their experimental set-up, thus potentially underestimating the actual impact forces.

Qualitative video analysis from match footage has shown that injury risk is increased if either the ball carrier or tackler or both players are moving at high speed (Fuller et al., 2010; McIntosh et al., 2010; Quarrie & Hopkins, 2008; Seminati, Cazzola, Preatoni, & Trewartha, 2015). Video analysis has also provided more details on what occurs in the short timeframe around the injury event. Impact force, direction, height and speed of the tackle have been identified as possible injury factors, with the risk increasing when there is a contact between the tackler's head/neck and shoulder and the ball carrier's lower limbs (McIntosh et al., 2010). It is essential, therefore, to investigate the nature and biomechanics of tackles with the long-term aim to develop more specific advice on how to execute effective rugby tackles with a reduced risk of injury.

Previous authors have analysed muscle activation during simulated rugby collisions such as scrums (Cazzola, Stone, Holsgrove, Trewartha, & Preatoni, 2015) and tackles (Herrington & Horsley, 2009; Morimoto, Sakamoto, Fukuhara, & Kato, 2013). In their studies they have highlighted the importance of muscle pre-activation to provide a rapid response to the impulsive external mechanical demands normally applied to the shoulder region and to offer protection of the anatomical structures. Furthermore, different spinal muscle activations influence head configuration prior to impact (Morimoto et al., 2013).

It is difficult to categorise how forces are transmitted during an impact when there are multiple bodies, multiple loading points, and multiple impacting structures with different elastic properties. The tackle event must be divided in different phases to understand the order the forces occur. Before the impact the tackler player recruits his muscles with a bottom-up pattern, while during the tackle impact, the forces acting on the player cause deformation of the bodies coming into contact and they propagate through the tackler's body from the contact point (shoulder/neck) to the ground. Just after the impact the force produced by the tackler to resist the ball carrier is transmitted through the kinetic chain, from the legs to the point of impact, while the tackler is moving forward. Also, the muscles surrounding the cervical spine may act through various activation strategies, anticipatory activation, co-contraction, and stiffening, to balance the head on the neck and to guarantee both movement and stability (Cheng, Lin, & Wang, 2008; Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014).

Rugby injury prevention programmes, such as RugbySmart (http://www.coachingtoolbox.co.nz/rugbysmart/tackling/) and Boksmart (http://boksmart.sarugby.co.za/), have advocated the need for continuing player/coach education to promote the use of legal and technically sound tackles (e.g. foot placement, trunk and head position) to minimise the risk of injury for both tackler and ball carrier. Additional analyses are required to develop the understanding of how different tackle techniques and tackle situations influence the loading of players' anatomical structures. Previous investigations carried out simulations of tackle events that were either not very representative of real conditions, or considered only limited measures (Herrington & Horsley, 2009; Morimoto et al., 2013; Pain et al., 2008; Usman et al., 2011). Furthermore, no study has described how the forces observed in the tackle are generated and absorbed by the kinetic chain.

Therefore, the purpose of this study was to investigate rugby tackling biomechanics under different tackle conditions, with a focus on the load experienced, on head and trunk motion and on neuromuscular activation strategies. The tackle conditions assessed the influence of laterality (dominant vs. non-dominant side tackling) and tackling approach (standing vs. moving) on players' movement and neuromuscular patterns, with a secondary objective to evaluate a more realistic experimental set up for the analysis of simulated rugby tackles under dynamic conditions. The hypothesis was that different tackling conditions/situations can influence the biomechanics of the tackle players, with higher impact forces when tackling on the dominant side due to a more assertive technique.

Methods

Study design

In a repeated measures design, a group of rugby union players performed multiple trials under three different simulated tackle conditions (independent factors) to assess the effect on impact forces, spinal muscle activity and kinematics (dependent variables).

The three tackle conditions were: i) from a stationary position, with the dominant shoulder; ii) from a stationary position, with the non-dominant shoulder; and, iii) moving forward, with the dominant shoulder (i.e. dynamic tackle with a 3-step run up to double foot stance before the tackle).

Participants

Sample size estimation for effect size analysis was conducted (Hopkins, 2006) and revealed that a minimum sample size of 12 players was required to achieve a 0.5% probability of type I and 25% of type II errors, as recommended for this type of analysis (Hopkins, 2006). Fifteen male community- and University-level Rugby Union players (age 23.5 ± 5.1 years, height 1.82 ± 0.06 m, mass 96.6 ± 12.9 kg) participated. All participants reported being right-side dominant (this was not an inclusion requirement), had a minimum of 3 years playing experience and no history of spinal injuries in the 12 months prior to testing. Ethical approval was obtained from the University of Bath Institutional Ethics Committee and all participants provide written informed consent prior to participation.

Experimental conditions and data collection

In each trial, a 110 cm (height), 50 kg (mass) punch bag was used as the ball carrier simulator, selected to mimic the effective mass of a ball carrier without considering the limbs (Milburn, 1995). The punch bag was tethered to a trolley travelling along an overhead metal truss and was manually accelerated by an operator pulling a rope attached to the trolley through a pulley system. The operator had previously practiced to repeatedly generate similar approach speeds of the punch bag at impact to reach a momentum that resembled the typical tackling scenario (Hendricks, Karpul, Nicolls, & Lambert, 2012).

The height of the centre of mass of the punch bag was adjusted for each participant, so that during the tackle the trunk was flexed approximately to a 120° angle between trunk and thigh, with a ‘shoulder above hips’ posture adopted. Each participant performed up to five sub-maximal trials to become familiar with each of the experimental conditions (i.e. punch bag simulator and different tackle types). They were advised to tackle as they would normally do on the field during a competitive match, but without taking the opponent (tackle bag) to the ground, in the attempt to mimic the first phase of what would become a tackle. After the familiarisation attempts, participants completed at least three successful trials in each of the three tackle conditions, up to a maximum of 20 trials in one session. Recovery intervals greater than 1 min~~ute~~ between consecutive trials were allowed to mitigate fatigue effects.

Following the tackling trials, each player performed two bilateral repetitions of 4 s isometric maximal voluntary contractions (MVC) of the upper trapezius, middle trapezius, erector spinae and gluteus maximus muscles, with a 1-minute break between each measurement (Cazzola et al., 2015; Hermens & Freriks, 1999), (Appendix, Table A).

Integrated measures of kinematic and kinetic variables were employed to characterise the tackle event, together with muscle activation analysis with a specific focus on the tacklers’ upper spine, shoulders, neck, and head regions. Four pressure sensors (Model #3005 VersaTek XL, FScan, Tekscan Inc, USA) were attached on the punch bag (Figure 1), to allow estimation of the impact forces during the tackle (sampling frequency 500 Hz). The impact force was assumed to be normal to the surface of the sensors applied on the punch bag, since no shear forces could be estimated from the available pressure sensors. As suggested by previous studies (Cazzola, Trewartha, & Preatoni, 2014; Pain et al., 2008; Usman et al., 2011) a dynamic calibration process was used to pre-calibrate the pressure sensors (Cazzola et al., 2014).

Participant and punch bag motion were captured through a 16-camera motion capture system (Oqus, Qualisys, Sweden) operating at 250 Hz. 8 reflective markers were positioned on the punch bag (Figure 1) and a 64-markers configuration was used to describe participants' segment kinematics (Table 1).

Eight wireless EMG electrodes (Delsys Trigno, Delsys Inc, USA), sampling at 1925 Hz, were attached bilaterally to: i) the Upper Trapezius (UP), 1 cm superior to the scapula spine midway between the medial origin of the scapula spine and the acromion; ii) the Middle Trapezius (MT), 2 cm medial to the medial edge of the scapular spine, at the level of T3; iii) the Erector Spinae (ES), 3.5 cm from the midline of the spine at the level of L4-5; iv) the Gluteus Maximum (GM), at 50% on the line between the sacral vertebrae and the greater trochanter (this position corresponds with the greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter) (Hermens & Freriks, 1999; Cazzola et al., 2015). Prior to mounting electrodes, the skin surface was prepared by shaving, lightly abrading and cleaning with alcohol wipes. Surface EMG signals were collected bilaterally on each participant using Delsys EMGworks 4.1.05 software (Delsys Inc, USA).

A control and acquisition system (cRIO-9024, National Instrument, USA) operating in real time and driven by specifically designed software (LabVIEW, National Instrument, USA) was used to synchronously trigger the acquisition software for all the devices, and all the data were time-aligned to give a thorough depiction of the biomechanical demands acting on the player under the different tackling conditions.

Data Processing

Raw pressure data from the individual pressure sensors were used to estimate contact forces. The overall force exerted on the tackler (F_{TOT}) was calculated as the sum of the single estimated forces of the four sensors on the punch bag. Spatial coordinates of the markers positioned on the player and the punch bag were exported and filtered with a 4th order, zero lag, low-pass Butterworth filter with a cutoff frequency of 16 Hz. Trunk absolute angles and relative joint angle for the neck (between head and trunk) were computed in Visual 3D (v5, C-Motion Inc, USA) in terms of flexion/extension, lateral bending and rotation. The coordinates of the 8 markers on the punch bag were used to estimate the geometrical centre ('G' in Figure 1) of the punch bag under the assumption that it can be represented as a rigid body of cylindrical shape and homogeneous density. Resultant punch bag velocity (v_{TOT}) was described as the velocity of its centre of mass and the horizontal component of velocity (v_{HOR}) was estimated as projection of v_{TOT} on the horizontal axis (Figure 1). After double checking from kinematics that there was no deceleration of the punch bag prior to contact, time at impact (t_{IMP}) was defined as the instant when v_{HOR} reached its highest value, while impact duration (dt) was estimated as

$$dt = t_{STOP} - t_{IMP}$$

where t_{STOP} corresponded to the time when punch bag horizontal velocity reached zero .

In addition, for each trial, the Impulse (I) of the collision was calculated as

$$I = \int_{t_{IMP}}^{t_{STOP}} F_{TOT} \cdot dt$$

Raw electromyograms were filtered by applying a 2nd order double pass, band-pass Butterworth filter between 30 and 200 Hz. Data were then rectified and smoothed using a moving average over 50 ms windows (LabVIEW 2013, National Instrument, USA). Raw EMGs were normalised to the relevant average MVC, which was calculated as the average rectified signal between 0.2 and 2.2 s after force had plateaued, following the initiation of the maximum isometric contraction. Two trials were included in the calculation of average MVC. Muscle activity (average normalised amplitude) during tackle trials was calculated over two phases of each tackle repetition: 0.04 s before impact to time of impact ('pre-impact time'); and for the entire duration (dt) of the impact ('impact time'). Time of EMG onset (onset time = t_{ON}) was included in the analysis for the stationary conditions and identified as the point at which 50 consecutive EMG samples (approximately 25 ms) exceeded 3 standard deviations from the mean baseline reference amplitude. Baseline EMG activity was defined as the lowest mean in a 100 ms period in the first second of the acquisition (Carter & Gutierrez, 2015).

Statistics

Mean values of forces, kinematics and EMG variables were calculated from the three successful trials for each player. Group averages and standard deviation for each tackle condition were then calculated for impact forces, impact duration, impulse, punch bag velocity, kinematics variables and EMG measures. For one participant the dynamic condition, was not included in the analysis, because data were not available. Effect sizes were used to assess differences between tackle conditions. The stationary dominant-side tackle was the reference condition and compared with the stationary non-dominant side tackle condition and the moving dominant-side tackle condition, respectively. For all effect sizes, 90% confidence intervals (CI) were calculated and magnitude-based inferences derived (Batterham & Hopkins, 2006). Effects sizes were interpreted on the following scale: < 0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2, large; and > 2.0, very large, (Hopkins, Marshall, Batterham, & Hanin, 2009). Thus, a threshold for a practically important effect was set at 0.2, with the values between -0.2 and +0.2 signifying a trivial effect. As 90% CI provide a range within which the true effect statistic is likely to fall, effects were considered to be substantially positive only if the effect statistic was greater than +0.2 and the lower confidence limit did not cross -0.2. Conversely, if the effect statistic was less than -0.2 and the upper confidence limit did not extend past +0.2, the effect was deemed substantially negative. An effect was considered unclear if the 90% CI crossed over both +0.2 and -0.2.

Results

Forces, velocities and related parameters

A total of 135 tackles were recorded with the maximal punch bag velocity on the sagittal plane (v_{HOR}) ranging from 3.0 to 4.0 m/s (Table 2). Although the mean v_{HOR} was comparable in the three conditions analysed, mean peak impact force was substantially higher in the stationary dominant (mean = 2.84 kN) than in the stationary non-dominant condition (mean = 2.44 kN; effect size ± 90% CI = 0.53 ± 0.40) and substantially lower in the stationary than in the dynamic condition (mean = 3.40 kN; effect size ± 90% CI = -0.96 ± 0.44) (Figure 2).

The average contact time (dt) was substantially shorter for the stationary dominant side condition (mean = 0.102 s) compared with the stationary non-dominant side condition (mean = 0.111 s; effect size ± 90% CI = -0.56 ± 0.36) and substantially longer compared to the dynamic dominant side tackle condition, (mean = 0.095 s; effect size ± 90% CI = 0.47 ± 0.42). The impulse of the total force was comparable in the three tackle conditions, with small effects found between dominant and non-dominant side condition (effect size ± 90% CI = 0.24 ± 0.42), and between stationary and dynamic condition (effect size ± 90% CI = -0.27 ± 0.29).

Kinematics

At tackle impact for all three conditions, cervical motion was characterised by simultaneous flexion, lateral bending away from the contact shoulder and rotation of the neck (Table 3). Mean neck flexion joint angle at impact was greater for stationary non-dominant tackles than for stationary dominant shoulder tackles (effect size ± 90% CI = -0.26 ± 0.36), and greater for dynamic dominant side condition than stationary dominant condition (effect size ± 90% CI = -0.34 ± 0.21). A large effect was observed for the neck lateral bending angle at impact, that increased in non-dominant side tackles over stationary dominant tackles (effect size ± 90% CI = -0.64 ± 0.46) (Figure 3).

All players were characterised by a moderate (~50 degrees) absolute trunk inclination angle when impacting the punch bag, but no difference was found between the three different conditions. In addition the absolute trunk segment lateral bending angle was lower (i.e. trunk more vertical) for the non-dominant tackle condition effect size ± 90% (CI =0.92 ± 0.42) and for the dynamic condition (effect size ± 90% CI =0.33 ± 0.44) than the dominant stationary condition (Table 3).

EMG data

Mean amplitude of the normalised EMG was evaluated for the four couples of muscles in the time periods before and after the time of impact t_{IMP} (Figure 4). For all tackle conditions, the trapezius muscles of the side making contact with the punch bag were substantially more activated than the trapezius muscles on the contralateral side. This behaviour was observed both before and after the impact for most tackle conditions and effect sizes ranged from 0.71 ± 0.54 to 2.20 ± 0.64, with the only unclear effect observed for the right upper trapezius.

Muscle of the lower spine and glutei showed the opposite behaviour compared with the trapezius muscles, with erector spinae and gluteus maximus of the contra-lateral side more activated than the muscles on the tackle side, both before and after the impact with the bag; effect sizes ranged from 0.61 ± 0.74 to 1.40 ± 0.54, with the only unclear effect observed for the left erector spinae during the impact phase.

Muscle activations in the stationary conditions were characterised by considerable pre-activation of all 8 measured muscles prior to the impact with the punch bag (Figure 5). Although some trivial effects were present, results indicated that the glutei activated substantially earlier than the other muscles of the kinetic chain, both for the right side of the body in the dominant tackle (effect sizes ranged from 0.52 ± 0.59 to 1.10 ± 0.62) and for the left side in the non-dominant tackle (effect sizes ranged from 0.97 ± 0.63 to 1.30 ± 0.58). Muscle activation tended to be higher during the dynamic tackle condition compared with the stationary dominant side tackle condition, although effect sizes were typically small and only substantial for the right gluteus maximum in the pre impact phase (effect size ± 90% CI = 0.45 ± 0.52).

Discussion and implications

This study has highlighted the differences in loading conditions that can be attributed to the dynamics of a rugby tackling movement and also reinforced previous research that suggested biomechanical quantities depend on whether the tackle is made with the dominant or non-dominant shoulder. The present analysis adds to the small body of literature on the biomechanics of rugby tackling and suggests that the peak forces are higher than found in previous direct measurements, potentially as a product of the attempt to improve the realism of the simulated tackle protocol.

In the current study, peak impact forces were 13% higher in the stationary dominant than in the stationary non-dominant side tackle. Usman et al (2011) reported impact forces 6% higher in the dominant side tackle and interpreted this as greater strength and skill on the dominant side. In the non-dominant condition, tacklers adopted a different biomechanical strategy and assumed a more passive behaviour to generate the impulse needed to stop the momentum of the punch bag. Impact force reached a higher peak when tacklers impacted the punch bag with the dominant side, whereas the duration of the impact was longer when players used their non-dominant side. In the non-dominant condition, tackles were also characterised by less control of the movement of the head that was more flexed and laterally bent compared with the dominant side condition. Conversely, the absolute lateral bending of the trunk in the dominant conditions increased, bringing the head to the side and away from the tackle contact. This behaviour of the dominant side condition more closely matches the guidelines for an effective and safe technique with the head aligned outside the trunk of the attacker, not in front (RugbySmart, http://www.coachingtoolbox.co.nz/rugbysmart/tackling/; Boksmart, http://boksmart.sarugby.co.za/).

The introduction of a more dynamic tackling situation, whereby the tackler could perform three steps before contacting the moving punch bag, also generated higher impact forces and lower contact times. This change could be expected considering that under such conditions the opposite momenta of the punch bag and the tackler, whose estimated average centre of mass velocity due to the forward movement was about 2.9 ± 0.3 m/s, sum up to a larger value. The position of the player in the dynamic tackle was characterised by a moderate increase in neck flexion, suggesting an increased risk for the player who should instead orient the face up and 'sight' the target to maintain the cervical lordosis and a more favourable neck posture for absorbing impact energies. Whilst in this dynamic condition, tackles were performed with the right shoulder, and the players were able to control the lateral bending of the neck as they did in the stationary dominant condition, this level of control was not maintained for the neck flexion. Dynamic conditions, such as the ‘open’ environment of game situations would not always allow players to easily maintain a stable control of the head and so ‘heads-up’ tackling positions are considered a key injury prevention message to reinforce.

Neuromuscular activation of neck and trunk muscles both in the stationary dominant and non-dominant side condition presented a ‘criss-cross’ recruitment pattern. The impact-side trapezius muscles of the tackler always presented higher activation compared with the other side. Simultaneously, impact-side erector spinae and gluteus maximus were less active than in the contralateral side. The observed muscle activations agree with the experimental posture of the player that stops the punch bag with the impact-side shoulder by mainly pushing with the contralateral leg (hip extension action), rotating the trunk and activating the erector spinae fibres (Figure 1 shows an example in the dominant-side condition). Muscle activations persisted at the same levels (%MVC) for the entire duration of the impact until the motion of the ‘ball carrier’ was stopped.

Muscle pre-activation (i.e. prior to impact) was recorded in each observed muscle, regardless of tackling condition, and followed a recruitment sequence that appears coherent with the kinetic chain of energy, in which the body is considered as a linked system of articulated segments. The forces necessary to stop the punch bag are transmitted, from the legs, hips and trunk, to the shoulder, by stiffening the muscles in a coordinated way until the time of impact; impact-side trapezius muscles are the last in the recruitment sequence, while the contralateral gluteus maximum and erector spinae are activated first. During tackle impact, the external applied load will lead to rapidly developing deceleration forces to stop the punch bag and a reverse wave of impact energies which need to be absorbed from the contact point (shoulder/neck) through the trunk segments. The whole body momentum of the tackler is caused by the contact forces with the ball carrier being transmitted from the contact point to the ground and simultaneous resistance forces from the tackler generating reaction forces by pushing against the ground. This behaviour is confirmed by the ground reaction forces profiles observed during the different phases of the impact (Figure 1). Before the impact, pre-activation of the muscles prepares the tackler for the impact and the ground reaction forces are equally distributed on the force platforms. The tackler orients his body segments towards the punch bag, increasing his momentum and at the impact the forces transmitted from the ball carrier are partially absorbed by the tackler who is pushed back and his momentum decreases. Only at t_{STOP}, we can observe an increased ground reaction force on the non-impact side platform that allows the tackler to resist the punch bag momentum and stop it.

Pre-activation can functionally lead to an increase in cervical and lumbar spine stiffness, and orientations of the body segments in the proper way, which may better prepare players' spinal structures for the high biomechanical loads placed upon the upper spine at impact. Eckner et al. (2014) reported that muscle pre-activation decreased neck acceleration when applying impulsive test forces to athletes' head movements, suggesting that stiffness and anticipatory activation reduce kinematic responses during collisions, with a protective effect on the cervical spine. Pre-activation times (t_{ON}) were longer than in other studies that analysed muscle activity in rugby scrummaging (Cazzola et al., 2015) and tackling (Herrington & Horsley, 2009). Results with the current protocol show that the anticipatory activity of the observed muscles starts approximately 300 ms before impact, suggesting it follows a mechanism found in other sport activities termed the 'internal feedback loop' (Ohta et al., 2014). This mechanism is functional to movement correction when the velocity of an oncoming target is variable, and it is characterised by a biphasic EMG activation pattern similar to the one we found in simulated tackling (Figure 6). Visual inspection of EMG traces demonstrated that this behaviour was common among all the players, especially for gluteus and erector spinae muscles. Therefore, tacklers might rapidly correct a muscle activation strategy in response to an error signal generated by a difference between the predicted impact time and delayed/anticipated impact time caused by small changes of the target (punch bag) trajectory and/or velocity.

The analysis of the forces, movements and neuromuscular activation patterns under different tackling conditions is fundamental to elucidate the strategies employed by tacklers as they prepare their bodies for the impact with the ball carrier. Tackling analysis is very challenging from a biomechanical perspective, due to the complexity in creating an ecologically valid experimental set-up and the difficulty in measuring impact forces under realistic scenarios. However, in this study we devised an experimental set up able to measure *in vivo* loads, motion, and neuromuscular activity experienced by players during simulated tackles. The tackle simulator replicated some of the conditions that are reported to be typical of a real tackle scenario (Hendricks et al., 2012). The velocity at which the punch bag met the tackler was within the range of the typical ball carrier velocity reported in previous research (Gabbett & Kelly, 2007; Gabbett & Ryan, 2009; Hendricks et al., 2012). Peak force appeared higher than the values reported in previous studies (Pain et al., 2008; Usman et al., 2011). However, these studies exploited different technologies and experimental protocols to measure peak/impact forces. In some cases pressure sensors were positioned on the shoulders of the tackler, but the sensor area was too small as large forces were generated up to and beyond the sensor boundary (Pain et al., 2008). Potentially, more reliable results were obtained in Usman's study, where forces were measured with a custom built pressure sensors plate incorporated in the punch bag. However the 'ball carrier' was a static tackle bag and also in this case the pressure sensors covered just a small area. Our experimental set up tried to overcome some of the limitations of previous research and to improve the ecological validity of the simulation. Four larger pressure sensors were used to have a better coverage of the possible area of contact (overall sensed area = 15 x 39 cm), and the punch bag was accelerated against the tackler so that the impact could happen under a dynamical situation that better mimicked realistic tackling conditions.

Limitations

Some limitations characterised this study. Since video-based investigations have reported that the majority of tackles are associated with highly dynamical occurrences, especially in the frontal direction (Fuller et al., 2010; McIntosh et al., 2010) we decided to start our analysis by focussing on frontal tackles. However, rugby tackles can occur from different directions during a real game (Fuller et al., 2010) and the alignment of the head is, anecdotally, a major factor in tackle injury mechanisms. Further studies should investigate the effects of the different approach angles for the ball-carrier – tackler dyad. Secondly, force estimation was carried out using what currently available technology offers, but could potentially be affected by some inaccuracies. We did not consider the effect of the tackler velocity on the viscoelastic behaviour of the impacting surfaces/materials, which could have a role in dynamic tackles. Also, shear forces were not considered due to the features of the pressure sensors and some trials could underestimate the impact force. The experimental protocol should be extended to allow the tackle to be fully completed, by including initial impact and the movement towards the ground. This would improve the ecological validity further, affecting the kinematics and the EMG activations in the latter part of the tackle. In addition musculoskeletal simulations driven by experimental data could help to estimate the loads experienced by the players also during high injury risk situations, like for example when the head and neck are on the ‘wrong’ side of the body at impact.

Conclusions

This study represents an initial step in the process of depicting the biomechanics of rugby tackles, with a specific focus on impact loading and activation profiles of spinal muscles. The biomechanical characteristics of simulated tackles have been evaluated by focussing on two factors: laterality and approach-to-impact technique. We identified differences in the loading conditions and in segment kinematics due to dominant versus non-dominant sides and due to speed of contact. Overall, tackle technique on non-dominant side tackles was less compliant with current technique recommendations in terms of trunk and head/neck positions and there may be utility in a specific coaching focus on non-dominant side tackles. The analysis of muscle activation patterns during tackling showed a high level of muscle pre-activation that may potentially mitigate the effect of loads on spinal posture, providing a rapid compensation in response to external forces and increasing stability. These findings may also inform training practice, such as in the conditioning of novice players with regards to preparing for involvement in live tackles. A controlled and organised recruitment of the trunk and neck muscles is crucial to deal with the tackle impact. However, tackles often occur in uncontrolled situations and further studies are necessary to identify the specific injury mechanisms present in rugby tackling. Data captured from simulated tackle events may inform studies based on musculoskeletal and finite element models aiming to describe internal loading in potentially injurious tackle scenarios. In this way it will be possible to understand how contact loads transmit across the anatomical structures and translate into mechanical stresses acting on the cervical spine and upper trunk of the player.

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References

Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *International Jounal of Sports Physiology and Performance,1*, 50-57.

Berge, J., Marque, B., Vital, J. M., Senegas, J., & Caille, J. M. (1999). Age-related changes in the cervical spines of front-line rugby players. *The American Journal of Sports Medicine, 27*(4), 422-429

Brooks, J. H., Fuller, C. W., Kemp, S. P., & Reddin, D. B. (2005). Epidemiology of injuries in English professional rugby union: part 1 match injuries. *British Journal of Sports Medicine, 39*(10), 757-766. doi: 10.1136/bjsm.2005.018135

Brown, J. C., Lambert, M. I., Verhagen, E., Readhead, C., van Mechelen, W., & Viljoen, W. (2013). The incidence of rugby-related catastrophic injuries (including cardiac events) in South Africa from 2008 to 2011: a cohort study. *BMJ Open, 3*(2). doi: 10.1136/bmjopen-2012-002475

Burstein, A. H., Otis, J. C., & Torg, J. S. (1982). Mechanisms and pathomechanics of athletic injuries to the cervical spine. *Athletic injuries to the Head, Neck and Face.* Edited by Joseph S. Torg (pp. 139-154). Philadelphia, Lea & Febiger.

Carter, S., & Gutierrez, G. (2015). The concurrent validity of three computerized methods of muscle activity onset detection. *Journal of Electromyography and Kinesiology, 25*(5), 731-741. doi: 10.1016/j.jelekin.2015.07.009

Castinel, B. H., Adam, P., Milburn, P. D., Castinel, A., Quarrie, K. L., Peyrin, J. C., & Yeo, J. D. (2010). Epidemiology of cervical spine abnormalities in asymptomatic adult professional rugby union players using static and dynamic MRI protocols: 2002 to 2006. *British Journal of Sports Medicine, 44*(3), 194-199. doi: 10.1136/bjsm.2007.045815

Cazzola, D., Stone, B., Holsgrove, T. P., Trewartha, G., & Preatoni, E. (2015). Spinal muscle activity in simulated rugby union scrummaging is affected by different engagement conditions. *Scandinavian Journal of Medicine and Science in Sports*. doi: 10.1111/sms.12446

Cazzola, D., Trewartha, G., & Preatoni, E. (2014). Time-based calibrations of pressure sensors improve the estimation of force signals containing impulsive events. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 228*(2), 147-151

Cheng, C. H., Lin, K. H., & Wang, J. L. (2008). Co-contraction of cervical muscles during sagittal and coronal neck motions at different movement speeds. *European Journal of Applied Physiology, 103*(6), 647-654. doi: 10.1007/s00421-008-0760-4

Duprey, S., Bruyere, K., & Verriest, J. P. (2007). Human shoulder response to side impacts: a finite element study. *Computer Methods in Biomechanics and Biomedical Engineering, 10*(5), 361-370. doi: 10.1080/10255840701463986

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine, 42*(3), 566-576. doi: 10.1177/0363546513517869

Fuller, C. W. (2008). Catastrophic injury in rugby union: is the level of risk acceptable? *Sports Medicine, 38*(12), 975-986. doi: 10.2165/00007256-200838120-00002

Fuller, C. W., Ashton, T., Brooks, J. H., Cancea, R. J., Hall, J., & Kemp, S. P. (2010). Injury risks associated with tackling in rugby union. *British Journal of Sports Medicine, 44*(3), 159-167. doi: 10.1136/bjsm.2008.050864

Gabbett, T., & Kelly, J. (2007). Does fast defensive line speed influence tackling proficiency in collision sport athletes? *International Journal of Sports Science and Coaching, 2*(4), 467-472. doi: http://dx.doi.org/10.1260/174795407783359731

Gabbett, T., & Ryan, P. (2009). Tackling technique, injury risk, and playing performance in high-performance collision sport athletes. *International Journal of Sports Science and Coaching, 4*(4), 521-533

Hendricks, S., Karpul, D., Nicolls, F., & Lambert, M. (2012). Velocity and acceleration before contact in the tackle during rugby union matches. *Journal of Sports Science, 30*(12), 1215-1224. doi: 10.1080/02640414.2012.707328

Hermens, E.J. & Freriks, B. (1999). European Recommendations for Surface Electromyography. Published by Roessingh Research and Development, Enschede, the Netherlands, 1999, ISBN 90-75452-14-4.

Herrington, L., & Horsley, I. (2009). Electromyographic analysis of selected shoulder muscles during a rugby football tackle. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy and Technology, 1*(1), 10. doi: 10.1186/1758-2555-1-10

Hopkins, W. G. (2006). A spreadsheet for estimating sample size for magnitude based inferences. Available from http://www.sportsci.org/2006/wghcom.htm [accessed before September 2015].

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*(1), 3-13. doi: 10.1249/MSS.0b013e31818cb278

Kuster, D., Gibson, A., Abboud, R., & Drew, T. (2012). Mechanisms of cervical spine injury in rugby union: a systematic review of the literature. *British Journal of Sports Medicine, 46*(8), 550-554. doi: 10.1136/bjsports-2011-090360

McIntosh, A. S., Savage, T. N., McCrory, P., Frechede, B. O., & Wolfe, R. (2010). Tackle characteristics and injury in a cross section of rugby union football. *Medicine and Science in Sports and Exercise, 42*(5), 977-984. doi: 10.1249/MSS.0b013e3181c07b5b

Milburn, P. D. (1995). The Rugby Tackle - A time for Review. *Journal of Physical Education of New Zealand, 28*(1), 9-15

Morimoto, K., Sakamoto, M., Fukuhara, T., & Kato, K. (2013). Electromyographic study of neck muscle activity according to head position in rugby tackles. *Journal of Physical Therapy Science, 25*(5), 563-566. doi: 10.1589/jpts.25.563

Ohta, Y., Nakamoto, H., Ishii, Y., Ikudome, S., Takahashi, K., & Shima, N. (2014). Muscle activation characteristics of the front leg during baseball swings with timing correction for sudden velocity decrease. *PLoS One, 10*(4), e0124113. doi: 10.1371/journal.pone.0124113

Pain, M. T., Tsui, F., & Cove, S. (2008). In vivo determination of the effect of shoulder pads on tackling forces in rugby. *Journal of Sports Science, 26*(8), 855-862. doi: 10.1080/02640410801910319

Pinsault, N., Anxionnaz, M., & Vuillerme, N. (2010). Cervical joint position sense in rugby players versus non-rugby players. *Physical Therapy in Sport, 11*(2), 66-70. doi: 10.1016/j.ptsp.2010.02.004

Przybyla, A. S., Skrzypiec, D., Pollintine, P., Dolan, P., & Adams, M. A. (2007). Strength of the cervical spine in compression and bending. *Spine (Phila Pa 1976), 32*(15), 1612-1620. doi: 10.1097/BRS.0b013e318074c40b

Quarrie, K. L., & Hopkins, W. G. (2008). Tackle injuries in professional Rugby Union. The *American Journal of Sports Medicine, 36*(9), 1705-1716. doi: 10.1177/0363546508316768

Seminati, E., Cazzola, D., Preatoni, E., & Trewartha, G. (2015). Evaluation of tackling biomechanics in rugby: video incident analysis and experimental set up. In: *XXXIII International Conference on Biomechanics in Sports - Poitiers, France*, 555-558

Usman, J., McIntosh, A. S., & Frechede, B. (2011). An investigation of shoulder forces in active shoulder tackles in rugby union football. *Journal of Science and Medicine in Sport, 14*(6), 547-552. doi: 10.1016/j.jsams.2011.05.006

Williams, S., Trewartha, G., Kemp, S., & Stokes, K. (2013). A meta-analysis of injuries in senior men's professional Rugby Union. *Sports Medicine, 43*(10), 1043-1055. doi: 10.1007/s40279-013-0078-1

Table 1: Description of the biomechanical model used for kinematic analysis. Only head, trunk and pelvis segments and markers have been used for the aims of this study. Information about other segments and markers are reported, but they will be used in future investigations.

Segments	**Description**
Head	Nasium, Vertex and Occipital Bone.
Trunk	Bilaterally, markers on Acromion and Iliac Crest. Additional markers applied on C7, T8, L5.
Pelvis	Bilaterally, markers on PSIS, ASIS and iliac crest.
Right and Left Upper Arm	4 markers clusters.
Right and Left Fore Arm	Medial and lateral elbow and Ulnar and Radial styloid process.
Right and Left Hand	Ulnar and Radial styloid process and on the hand, just below the third metacarpus.
Right and Left Thigh	Greater trochanter, lateral and medial knee and 4 markers cluster.
Right and Left Shank	Medial and lateral knee, medial and lateral malleolus and 4 markers cluster.
Right and Left Foot	Medial and lateral malleolus, heel, 1st metatarsal and 5th metatarsal.

Table 2. Overall impact forces (in kN and normalised to body weight, BW) exerted on the tackler (F_{TOT}); impulse (*I*); peak velocities: resultant punch bag velocity (v_{TOT}) and horizontal component of velocity (v_{HOR}) as a projection of v_{TOT} on the horizontal axis; contact time durations (*dt*) for each of the three tackle conditions (mean ± SD). * indicates a substantial difference with the dominant side condition. Details in Figure 2.

		Dominant Side	**Non-Dominant Side**	**Dynamic**
F_{TOT}	(kN)	2.84 ± 0.74	2.44 ± 0.64*	3.40 ± 0.86*
F_{TOT}	(BW)	2.93 ± 0.74	2.57 ± 0.57*	3.62 ± 0.79*
I	(kN·s)	0.170 ± 0.030	0.163 ± 0.028	0.178 ± 0.033
v_{TOT}	(m/s)	3.76 ± 0.24	3.70 ± 0.25	3.73 ± 0.31
v_{HOR}	(m/s)	3.74 ± 0.24	3.68 ± 0.25	3.71 ± 0.30
dt	(s)	0.102 ± 0.012	0.111 ± 0.021*	0.095 ± 0.020*

Table 3. 3D angles (in degrees) for the head segment relative to the trunk (neck angle), and trunk absolute angles (mean ± SD), for the three tackle conditions at time of impact (t_{IMP}). * indicates a substantial difference with the dominant side condition. Details in Figure 3.

	Dominant-Side	Non-Dominant-Side	Dynamic
Neck			
Flexion	22 ± 15	27 ± 19*	27 ± 15*
Bending	12 ± 9	18 ± 10*	12 ± 8
Rotation	14 ± 10	16 ± 15	13 ± 11
Trunk			
Flexion	52 ± 10	52 ± 11	52 ± 10
Bending	23 ± 6	18 ± 5*	20 ± 10*
Rotation	23 ± 13	21 ± 15	21 ± 18

Figure Legends

Figure 1: Position of the 4 pressure sensors on the Punch Bag (left panel). Graphical representation of the punch bag horizontal velocity component (v_{HOR}), as projection of v_{TOT} on the horizontal axis in the sagittal plane. G indicates the geometrical centre of the punch bag, assuming the cylindrical shape and homogeneous density. Black arrows indicate the ground reaction forces respectively recorded at onset times (t_{ON}), impact time (t_{IMP}) and at the time when punch bag horizontal velocity reached zero (t_{STOP}).

Figure 2: Differences (effect sizes ± 90% CI) in overall peak force (F_{TOT}) exerted on the tackler, impulse (*I*), punch bag (PB) horizontal velocity component (v_{HOR}), as projection of v_{TOT} on the horizontal axis, and contact times (dt). (A) Dominant-Side vs. Non-Dominant-Side condition. (B) Dominant-Side vs. Dynamic condition. Dominant-Side tackle is the reference condition and bars represent 90% confidence intervals. Central area (0.0 ± 0.2) indicates a trivial effect. Percentages in brackets represent the likelihood that the effect (right vs. left condition) is negative | trivial | positive.

Figure 3: Differences (effect sizes ± 90% CI) in the 3D angles reported in Table 3. (A) Dominant-Side vs. Non-Dominant-Side condition. (B) Dominant-Side vs. Dynamic condition. Dominant-Side tackle is the reference condition and bars represent 90% confidence intervals. Central area (0.0 ± 0.2) indicates a trivial effect. Percentages in brackets represent the likelihood that the effect (right vs. left condition) is negative | trivial | positive.

Figure 4: Mean amplitude of the EMG activities expressed as %MVC for the four couple of muscles, Upper Trapezius (UP), Middle Trapezius (MT), Erector Spinae (ES) and Gluteus Maximum (GM) for the dominant side-right shoulder tackle (black bars), the non-dominant side-left shoulder tackle (grey bars) and for the dynamic condition-right shoulder (white bars). Two different phases are reported: 0.04 s before the impact (pre-impact time) and during the impact time dt (impact time). * denotes substantial difference between dominant and non-dominant side tackle. ^ denotes substantial difference between stationary dominant side and dynamic tackle condition.

Figure 5: Mean onset times (t_{ON}) prior to impact for left (upper panel) and right (lower panel) muscles -Upper Trapezius (UP), Middle Trapezius (MT), Erector Spinae (ES) and Gluteus Maximum (GM)- for the dominant side-right shoulder tackle condition (black lines and full black circles) and for the non-dominant-left shoulder tackle condition (grey lines and empty grey squares), when the players were in the stationary position. 't' denotes a trivial effect between muscles onset times.

Figure 6: Biphasic EMG activation (%MVC) of Left and right Gluteus Maximum during a stationary non-dominant tackle. Black arrows highlight the biphasic pattern before the impact.

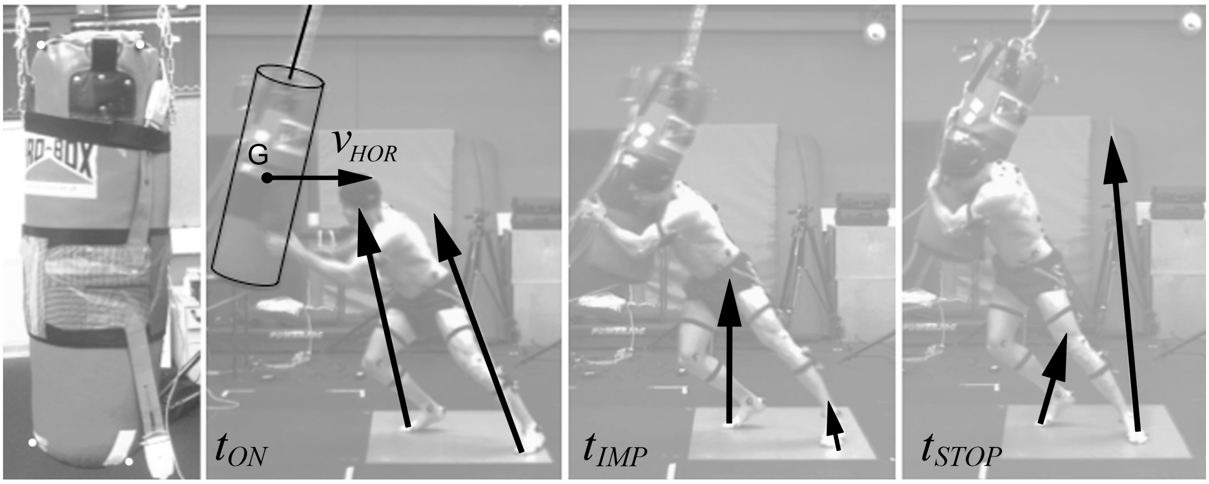

Figure 1

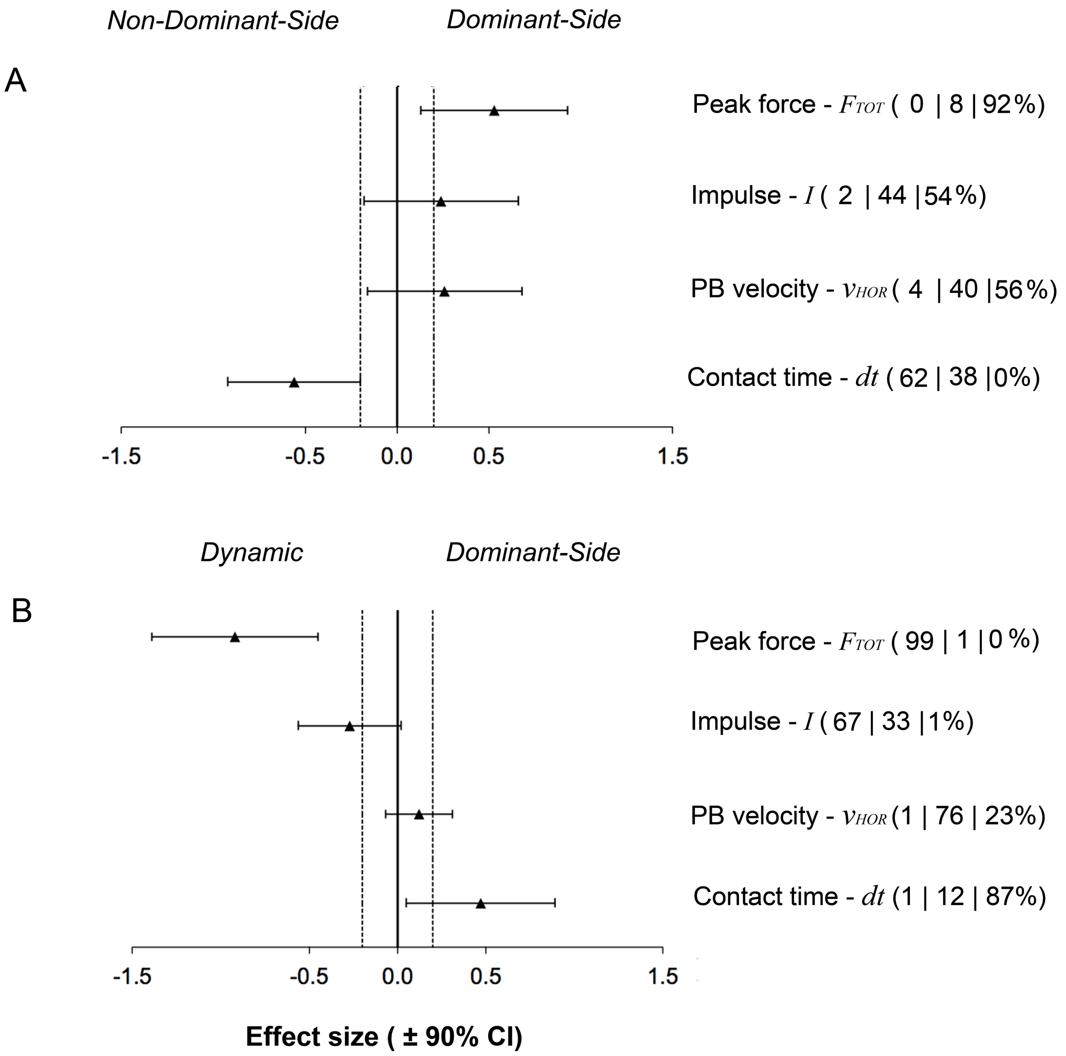
Non-Dominant-Side
Dominant-Side
A
Peak force - F_{TOT} (0 | 8 | 92%)
Impulse - I (2 | 44 |54%)
PB velocity - v_{HOR} (4 | 40 |56%)
Contact time - dt (62 | 38 |0%)
-1.5
-0.5
0.0
0.5
1.5
Dynamic
Dominant-Side
B
Peak force - F_{TOT} (99 | 1 | 0 %)
Impulse - I (67 | 33 |1%)
PB velocity - v_{HOR} (1 | 76 | 23%)
Contact time - dt (1 | 12 | 87%)
-1.5
-0.5
0.0
0.5
1.5
Effect size (± 90% CI)

Figure 2

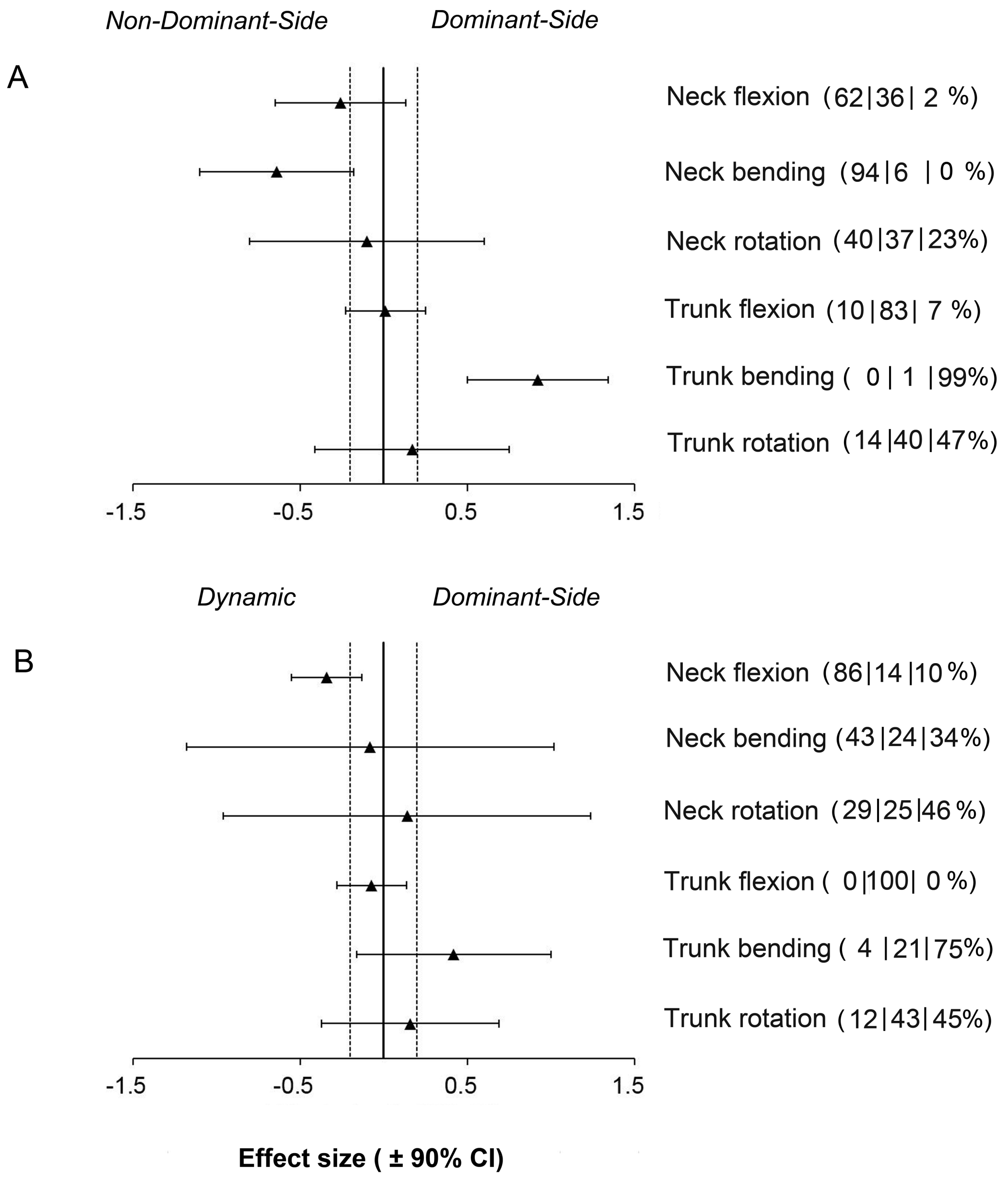
Non-Dominant-Side
Dominant-Side
A
Neck flexion (62|36| 2 %)
Neck bending (94|6 | 0 %)
Neck rotation (40|37|23%)
Trunk flexion (10|83| 7 %)
Trunk bending (0| 1 |99%)
Trunk rotation (14|40|47%)
-1.5
-0.5
0.5
1.5
Dynamic
Dominant-Side
B
Neck flexion (86|14|10 %)
Neck bending (43|24|34%)
Neck rotation (29|25|46 %)
Trunk flexion (0|100| 0 %)
Trunk bending (4 |21|75%)
Trunk rotation (12|43|45%)
-1.5
-0.5
0.5
1.5
Effect size (± 90% CI)

Figure 3

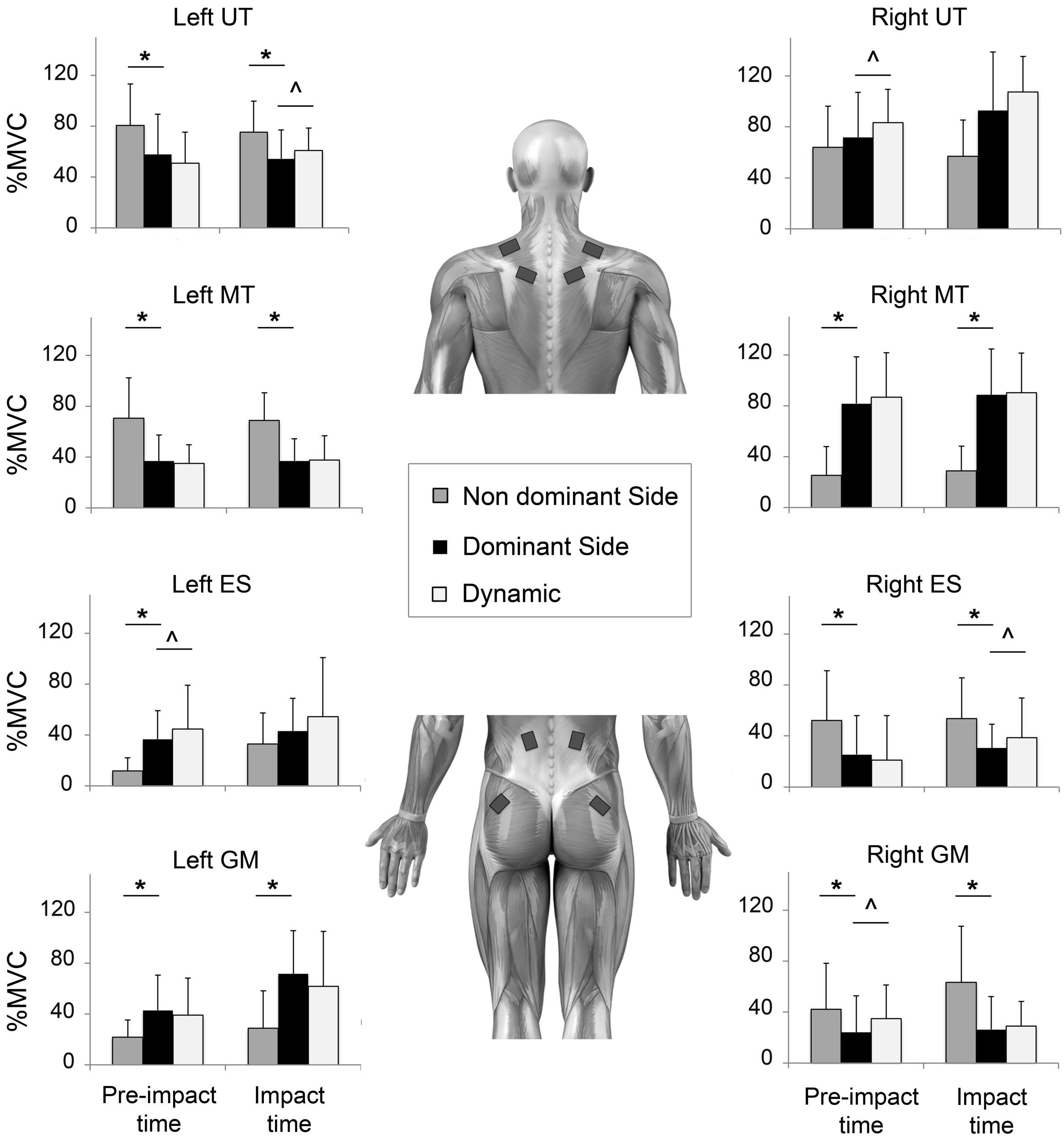
Left UT
Right UT
Left MT
Right MT
Left ES
Right ES
Left GM
Right GM
%MVC
0
40
80
120
*
^
Non dominant Side
Dominant Side
Dynamic
Pre-impact time
Impact time

Figure 4

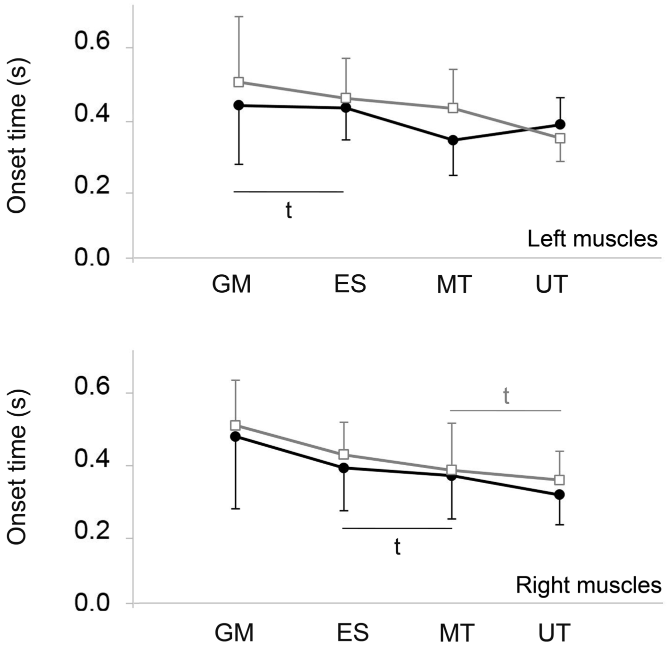
0.6
0.4
0.2
0.0
Onset time (s)
t
Left muscles
GM
ES
MT
UT
0.6
0.4
0.2
0.0
Onset time (s)
t
t
Right muscles
GM
ES
MT
UT

Figure 5

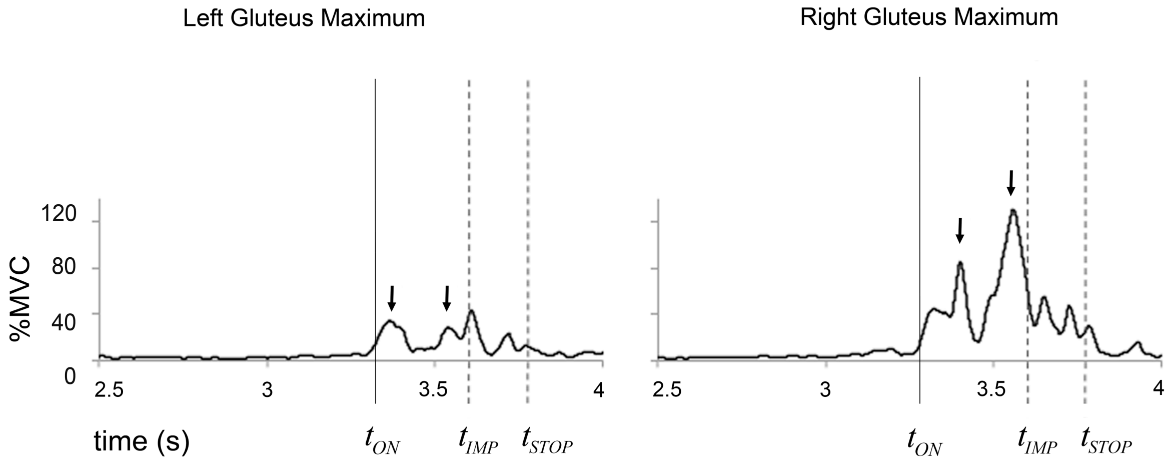
Left Gluteus Maximum
Right Gluteus Maximum
%MVC
120
80
40
0
2.5
3
3.5
4
2.5
3
3.5
4
time (s)
t_{ON}
t_{IMP}
t_{STOP}
t_{ON}
t_{IMP}
t_{STOP}

Figure 6

APPENDIX:

Table A: Positions and resistances used to measure MVC for the upper trapezius, middle trapezius erector spinae and gluteus maximus (Cazzola et al., 2015; Hermens & Freriks, 1999).

Muscle	**Description**
Upper Trapezius	Participant lies in a prone position with both arms abducted at the shoulder (~45°) and externally rotated with the elbow flexed. The participant attempts to abduct the arms against manual resistance applied to the elbow.
Middle Trapezius	Participant lies in a prone position. The elbow extensors and the posterior shoulder muscles must give necessary fixation in order to use the arm as a lever. The participant attempts to perform a lateral rotation of the scapula, with shoulder abduction against manual resistance. To obtain this position of the scapula and to obtain leverage for the test, the elbow needs to be extended and the shoulder placed in 90 degrees abduction and lateral rotation.
Erector Spinae	Participant lies in a prone position with the torso on the table and the legs projected horizontally over the end of the table. The participant attempts to extend the lower trunk and hip against manual resistance applied to the posterior thigh.
Gluteus Maximus	Participant lies in a prone position on the table and the legs projected horizontally. The participant attempts to extend the hip against manual resistance applied to the posterior shank.