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Biomechanics of the shoulder girdle: a case study on the effects of union rugby tackles

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Purpose: The shoulder girdle is a complex system, comprised by a kinematic chain and stabilizers. Due to the delicate equilibrium and synchronism between mobility and stability, high external loads may compromise its physiology, increasing the risk of injuries. Thus, this study intends to fully characterize the effects of a rugby tackle on the shoulder's anatomy and physiology. *Methods*: For the experimental procedures, a matrix of pressure sensors was used, based on the Teckscan® pressure in-soles, force plates, an isokinetic dynamometer and sEMG (surface electromyography). *Results*: The anterosuperior region of the shoulder girdle confirmed the highest pressure values during impact (100 kPa–200 kPa). Also, the right and left feet performed a vertical peak force of 1286 N (1.4 BW) and 1998 N (2.21 BW), respectively. The muscular activity of the shoulder muscles decreased after performing multiple tackles. *Conclusions*: During a tackle, the clavicle, scapula, trapezius and acromioclavicular joint are the anatomical structures with higher risk of injury. Also, the strike force on the feet decreases for stability purposes. After performing multiple impacts the muscular activity of the trapezius and rotator cuff muscles decreases, which may lead, in the long-term, to instability of the shoulder and inefficiency of the scapulohumeral rhythm.

Key words: *shoulder, rotator cuff, pressure sensors, force plates, isokinetic dynamometer, sEMG*

1. Introduction

The main functions of the shoulder complex consist in the positioning of the hand along the different anatomical planes as well as materializing the link between the axial and appendicular skeleton [4]. For that reason, it is comprised of elements that promote not only its mobility (e.g., type of connection between appendicular and axial skeleton, existence of a kinematic chain and morphology of the joints surfaces) but also its stability [4], [12], [24].

This last topic is particularly relevant in terms of the physiology and anatomy of the glenohumeral joint (one of the main joints of the shoulder and the most mobile in the human body). The stabilizers can be grouped in two different types: static, which are responsible for assuring the integrity of the joint in the initial and final stages of arm movements, and dynamic, which grant the stability of the joint during the arm motion [4], [12]. The static stabilizers are comprised of the glenohumeral ligaments, synovial liquid, negative intra-articular pressure and the glenoid *labrum*, while the dynamic stabilizers are mainly composed of muscular structures, where the rotator cuff muscles (supraspinatus, infraspinatus, teres minor and subscapularis) play a leading role [12], [22], [24]. Therefore, the dynamic stability is achieved due to the compression forces exerted from the muscles, which materializes the concavity compression concept (compression of the head of the humerus towards the glenoid). The efficiency of this mechanism is determined by the ratio established between the different forces applied in the proximity of the glenohumeral joint (compression, anterior/posterior and superior/inferior forces) [12], [14], [24]. The dynamic stability is also

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a function of the muscular stiffness and tendon compliance [12].

In addition to ensuring the arm's movements, and complement the stability of the glenohumeral joint, the shoulder muscles are also important for the scapulohumeral rhythm, especially the scapula rotators (trapezius and serratus anterior) [24]. The rhythm characterizes the coordinated movement of the humerus and scapula during arm elevation – this synchronism is important in order to avoid anatomical conflicts during arm elevation (e.g., subacromial impingement) [4], [24].

Since the different stabilizers and active muscles work in a coordinated and synchronous way during the arm movements, external loads directly applied in the shoulder may lead to traumatic, or atraumatic, events [22]. For that reason, on contact sport athletes, such as rugby players, the numerous contact events during a game tend to jeopardise the synergy and biomechanical equilibrium inherent to the shoulder complex [8], [9].

The shoulder girdle is particularly requested during rugby tackles, since the tackler tends to flex and abduct the arms (approximately 90°) in order to reach the opponent's torso [9]. That way, the impact force has an anterior/posterior direction which may lead to traumatic disorders or glenohumeral instability [9]. Due to its configuration and requirements, tackling is the contact event that leads to a larger number of shoulder pathologies [8], [20]. Epidemiologic studies proved that around 33% to 50% of total game injuries are due to tackle events, and 66.3% of those materialize as shoulder injuries in both the tackler and the ball carrier [20]. Among the different shoulder pathologies identified during a rugby game, the most common due to tackle events are: hematomas, acromioclavicular joint injuries, rotator cuff injuries and dislocation, or subluxation, of the glenohumeral joint [8], [20]. Recent studies have also identified an eventual accumulation of micro-traumas (due to the successive impacts that occur during a rugby game) that compromise the muscular synergy and the effectiveness of the neuromuscular system [10], [16]. This situation decreases the proprioceptive feedback of the athlete's shoulder and may lead to pathologies in the long term [10], [16].

The effects that a tackle has on the anatomy and physiology of the shoulder complex is still a theme that needs more concern and research, despite recent studies have already quantified the impact forces, attained the pressure distribution in the shoulder and evaluated the advantages of shoulder pads [18], [21]. Thus, in order to have a better understanding perception of the mechanisms related to shoulder injuries and the response of the human body during the impact with the ball carrier, an experimental procedure was established composed by two distinct, sequential, phases.

1st Phase – Biomechanics of a tackle event

By using force plates and pressure transducers, the pressure distribution in the shoulder during a tackle, the impact force on the athlete's shoulder and the athlete's feet strikes parameters were determined. Hence, it was possible to determine the regions of the shoulder with higher risk of injuries and also establish a relationship between types of feet strikes and the tackling mechanisms.

2nd Phase – Tackle effects on shoulder's physiology

Evaluation of the damages on the shoulder's muscular structures (due to a successive set of tackles) using sEMG and an isokinetic dynamometer. This way, it was possible to perceive decreases in muscular activity and in strength generation ability, which can lead, in the long-term, to shoulder pathologies.

Despite being composed of two different phases, executed in a sequential way, it is important to highlight the interchangeability of the experimental results from both phases.

2. Methods

The study was conducted in the laboratory using a rugby tackling shield. The sample consisted of a single athlete, from which a written informed consent was obtained and who was provided with all the information needed. The rugby player's weight was, approximately, 92.1 kg, and he was 1.88 m tall. He is a senior forward player (flanker), from a Portuguese first league team, with his right side being his dominant side. The study was approved by the University of Porto Ethics Committee (Parecer 10/CEUP/2015).

2.1. Biomechanics of a tackle event

For the first phase of the case study, resistive force plates (Bertec® models, FP 4060-15 and FP 6090-15), embayed in the laboratory floor, and Teckscan® pressure in-soles (F-Scan models, 3000E) were used in a synchronous way. Since these pressure transducers have an FSR nature and a high spatial resolution, it was possible to adjust the matrix sensors to the shoulder complex in order to attain the pressure distribution, and force, during the impact. The force plates allowed the obtaining of kinetic information (F_x, F_y, F_z) necessary for characterizing the athlete's feet strikes while tackling.

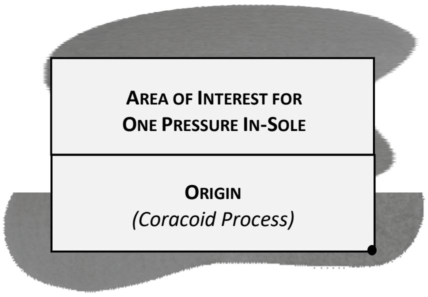

Fig. 1. Scheme of the global area of interest set from the F-Scan pressure in-soles

The synchronization of the equipment was achieved by using a trigger system while a step calibration method was used for the pressure matrix.

The data collected by the equipment's software was filtered using a Matlab® routine. For the pressure results, it was necessary to spatially reorganize the information of each individual sensor of the matrix and attain a pressure distribution that was coincident with the area of the shoulder that was instrumented. Only by doing so was it possible to evaluate the pressure distribution at the instant where the impact force was the highest, as well as the maximum pressure distribution and the impact force evolution.

In terms of the kinetic information from the force plates, two transformation matrices (due to the curvi-

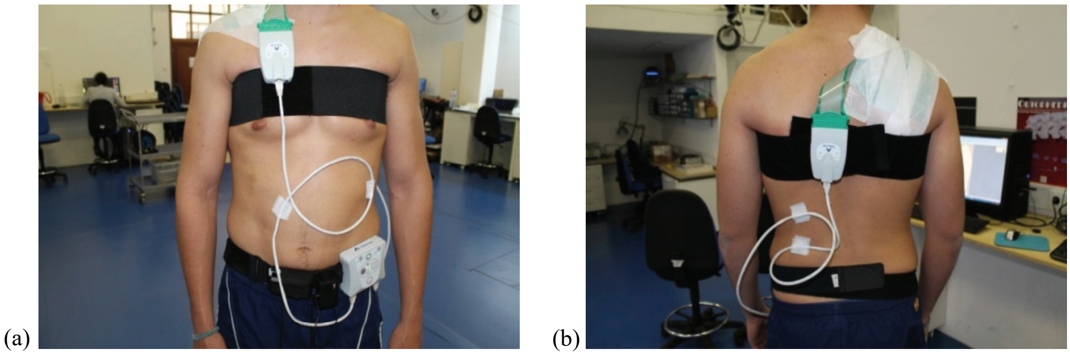

Fig. 2. (a) Custom made sensors matrix allocated in the athlete's shoulder; (b) Teckscan® acquisition system

To adjust the settings of the F-Scan pressure insoles for the present application, it was set for each pressure in-sole a rectangular area, eliminating all the individual pressure sensors that laid outside that region (Fig. 1) – attainment of a regular, rectangular, matrix of pressure sensors. By juxtaposing two modified pressure insoles, it was possible to increase the global measuring area. To guarantee the standardization and uniformity of the pressure sensors' allocation process the coracoid process as the origin of the matrix and an orientation similar to the glenohumeral line were defined (Fig. 2a and 2b).

The force plates allowed recording the forces from the two feet strikes closer to the impact. For that reason, the tackle events were performed so that the results from each foot strike were collected by different force plates: force plate number 3 recorded the front foot strike (right foot), and force plate number 1 recorded the back foot strike (left foot), Fig. 3. A maximum run-up distance of 2 m was set and the athlete was asked to tackle the shield a total of five times [18], [21]. Since the athlete needs to perform a lateral approach before tackling, a curvilinear trajectory was set according to the laboratory facilities, Fig. 3.

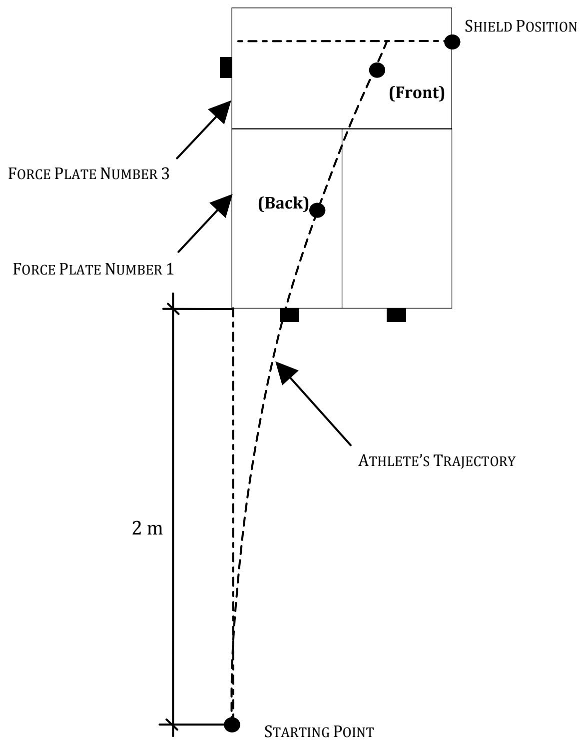

Fig. 3. Diagram of the tackles conducted in the laboratory for the first phase of the study (superior view)

linear trajectory of the athlete) were incorporated in the routines which allowed the analysis of the forces in the athlete's anatomical referential. Digital filters were also implemented in order to minimize the effect of noise – fourth order Butterworth filter with a cut-off frequency of 20 Hz [13].

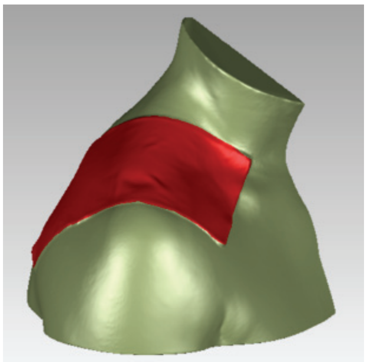

Fig. 4. Diagram of the tackles conducted in the laboratory for the first phase of the study (superior view)

Using a 3D scanner and model manipulation softwares, a 3D model of the athlete's shoulder was developed in order to attain a more efficient representation of the shoulder's pressure distribution during tackles. In other words, the pressure data recorded by the modified in-soles and filtered by the Matlab® routine was spatially reorganized, so that we could have a 3D perspective of the pressure on the athlete's shoulder during a tackle event as this helps to identify its critical regions and structures (Fig. 4).

2.2. Tackle effects on shoulder's physiology

In order to evaluate the physiological effects that tackling has on the shoulder complex, an experimental procedure was also established where the athlete performed arm movements on BIODEX® (isokinetic dynamometer) with sEMG (Delsys® electrodes and system – Trigno™ Wireless EMG System) placed on eight shoulder muscles, before and after being asked to tackle the shield fifteen times, without any recuperation time between trials.

To guarantee the synchronization of the outputs, some of the results from BIODEX® (torque, range and speed of the arm movement) along with the muscle activity were registered, simultaneously, by Qualisys Motion Capture System.

For the isokinetic dynamometer tests, the arm abduction/adduction and internal/external rotation (arm abducted 90°) as main movements were selected, at 60 °/s. It was set to five repetitions per movement, since a "strength speed" was selected and we wanted to minimize the fatigue induced on the athlete. The range of motion was defined according to the athlete's level of comfort. The abduction/adduction movements started with the arm fully adducted while the internal/external rotations started with the arm fully rotated, internally.

For the surface electromyography, the superficial shoulder muscles were instrumented with eight active electrodes (superior, inferior and transverse trapezius; posterior, anterior and middle deltoid; latissimus dorsi; clavicular portion of the pectolaris major). The position of the sensors along the muscle was set according to the SENIAM project and Meskers' study [15] (Fig. 5). The athlete's skin was cleaned with ethyl alcohol (90%) and all dead cells were later removed by using an adhesive [2]. After bonding each sensor to its respective muscular portion, the limits of the electrodes were marked on the skin of the athlete, so that, after performing the arm movements on the isokinetic dynamometer, the electrodes could be removed for the impacts and later replaced [7].

The athlete performed MIVC (Maximal Isometric Voluntary Contractions) tests according to Boettcher's results [3], in order to normalize the sEMG data.

In order to accomplish a quantitative and qualitative evaluation of the muscle activity during the arm movements, a Matlab® routine was created, which allowed obtaining the EMG envelop and the activation and deactivation time for each instrumented muscle [2].

(a) (b) (c)

Fig. 5. Electrodes position along the shoulder muscles: (a) anterior view; (b) lateral view; (c) posterior view

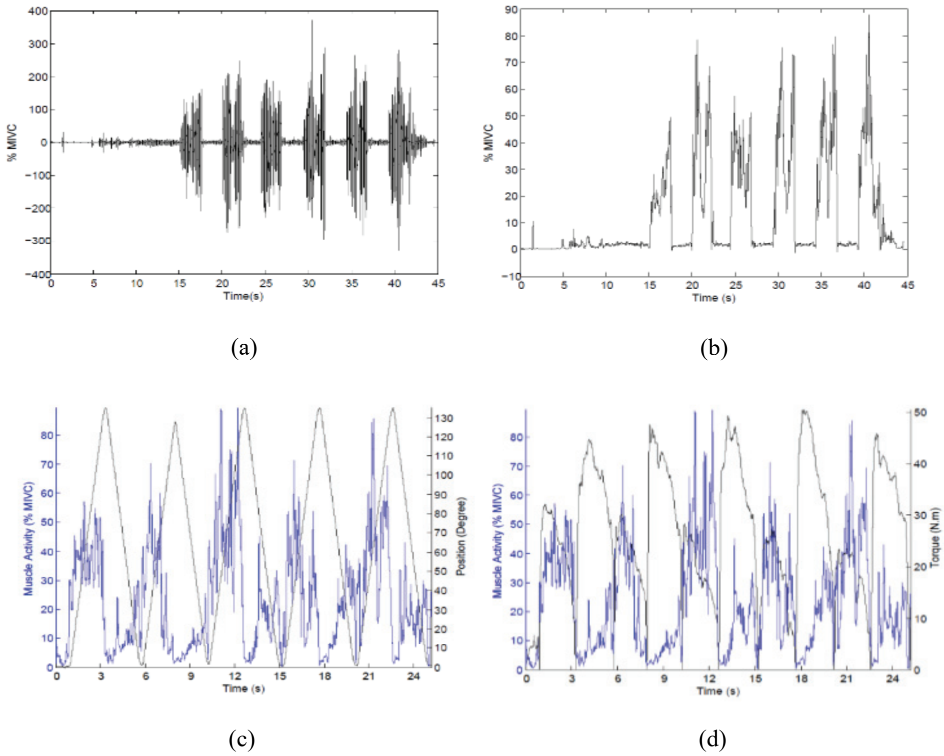

Fig. 6. sEMG outputs from Matlab® routines: (a) raw sEMG; (b) smooth sEMG; (c) sEMG vs amplitude signal; (d) sEMG vs torque signal

It performs a digital filtering, using a low and high pass Butterworth filter, with 30 Hz and 450 Hz as cut-off frequencies, respectively (minimizes the effect of the motion artifact and baseline noise contamination) [6]. The routine proceeds by removing the bias in the signal and performing a full-wave rectification in order to preserve the energy of the signal [2]. Finally, it is smoothed using the linear envelope method [2] (Fig. 6).

The activation and deactivation times are usually determined using a threshold. However, in this particular case, since the muscles contractions are mainly dynamic, the threshold is set using a default movement amplitude 2°. For that reason the final electromyographic parameters (maximum muscular activity, time to peak, average activity, duration of the movement and electric impulse) are the function of the arm movement's evolution, instead of the individual muscular contractions.

3. Results

3.1. Biomechanics of a tackle event

The reference pressure distribution, for maximum impact force instant, is presented in Fig. 7a. The pressure results are in between [100; 200] kPa. Nevertheless, all the distributions obtained from the tackle trials had discrete areas with pressure values that were not reliable, since they were far greater than 200 kPa and had a discrete arrangement instead of a blur. Thus, in order to verify the consistency of the data from those regions (identified in Fig. 7a) we performed a new set of five tackles using eight individual pressure sensors (Walkinsense®) placed on the shoulder's areas where the atypical data was collected. The results from the Walkinsense® tests showed that the pressure values on those areas was within the previously defined limits [100 kPa; 200 kPa], instead of the 300 kPa recorded by the modified pressure sensor matrix – the allocation process of the matrix created pre-stressed regions before the start of the trials. Thus an adaptation of the reference pressure distribution was made (Fig. 7b) using an iteration method to replace the misleading pressure values.

Figure 8 has the final average pressure distribution spatially reorganized on the 3D model of the athlete's shoulder. The final pressure values are in between [0; 200] kPa and the higher values are focused in the superior/intermediate region of the complex.

The average evolution of the impact force is represented in Fig. 9. It clearly represents a high energy impact situation, since it is possible to define a peak

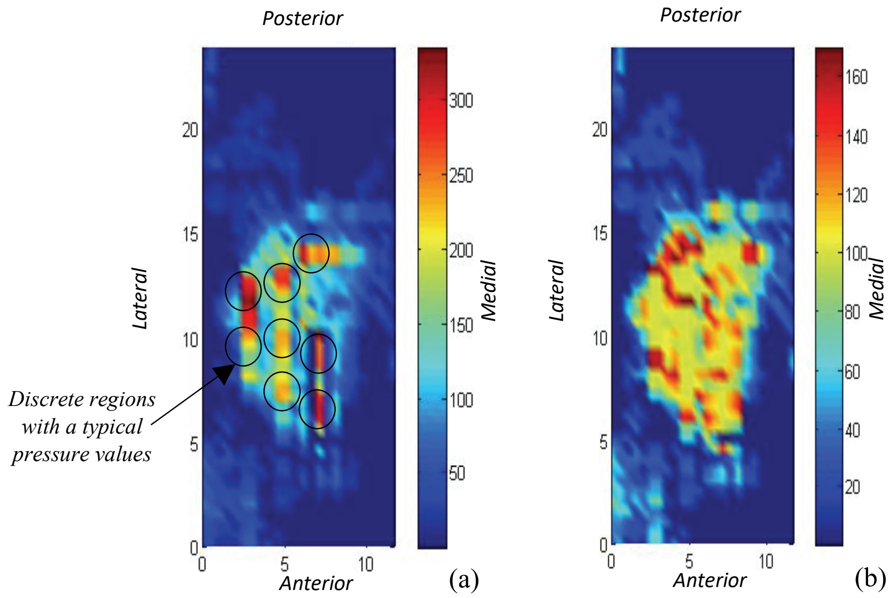

Fig. 7. Reference pressure distributions (instant of maximum impact force):
(a) original pressure distribution; (b) final distribution

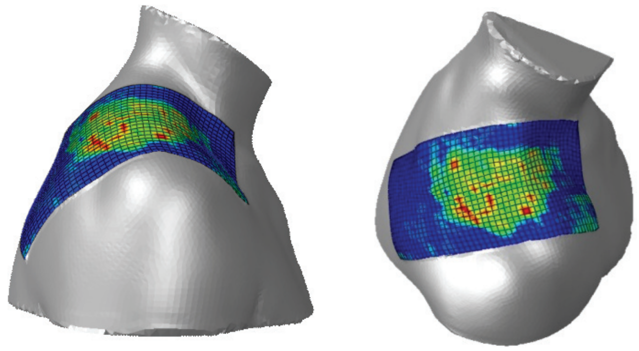

Fig. 8. 3D representation of the final reference pressure distribution (instant of maximum impact force): (a) lateral view; (b) superior view

value and the time span is small. The average peak force is of approximately 1279 N (SD = 114), or 1.4 BW (SD = 0.1), and the average time to peak value is 0.05 s (SD = 0.02). It is important to highlight that the duration of the impact situation is rather small because it was considered that a tackle event occurred whenever the athlete made the first contact with the tackling shield, it not being necessary, for matters of safety, to conduct the opponent to the floor.

In terms of the feet strikes performed by the athlete during the tackle events, the vertical, medial/lateral and anterior/posterior force components are presented in figure 10.

The vertical force's evolution is described in Fig. 10a and b. The left, and back, foot has an average maximum peak force of 1998 N (SD = 57), or 2.21 BW (SD = 0.1), while the right, and front, foot has an average maximum peak force of 1286 N (SD = 40), or 1.4 BW (SD = 0.04). The vertical component of a foot strike is especially important since it allows evaluating the foot strike pattern of the athlete during a tackle (by using the force evolution), the athlete's weight, his run-up speed (by using the peak force value) and the area of the foot in contact with the floor (by using the area below the force's evolution) [13].

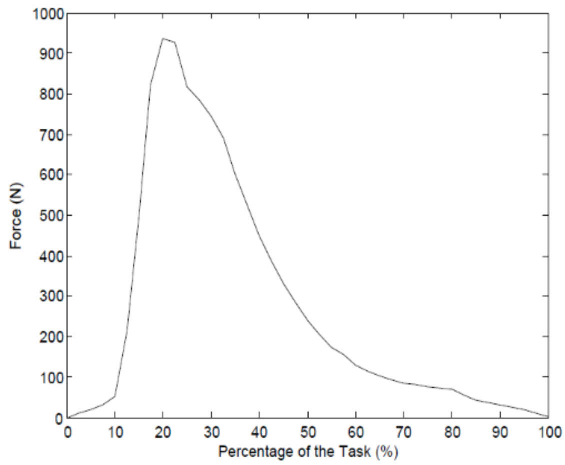

Fig. 9. Average impact force evolution with time

In Figs. 10c–f the medial/lateral and anterior/posterior force evolutions for both back and front feet are described. The average maximum value for the medial/lateral component is, for the back foot, 279 N (SD = 24), or 0.31 BW (SD = 0.03), and for the front foot 233 N (SD = 58), or 0.26 BW (SD = 0.06). On the other hand, the maximum average value of the

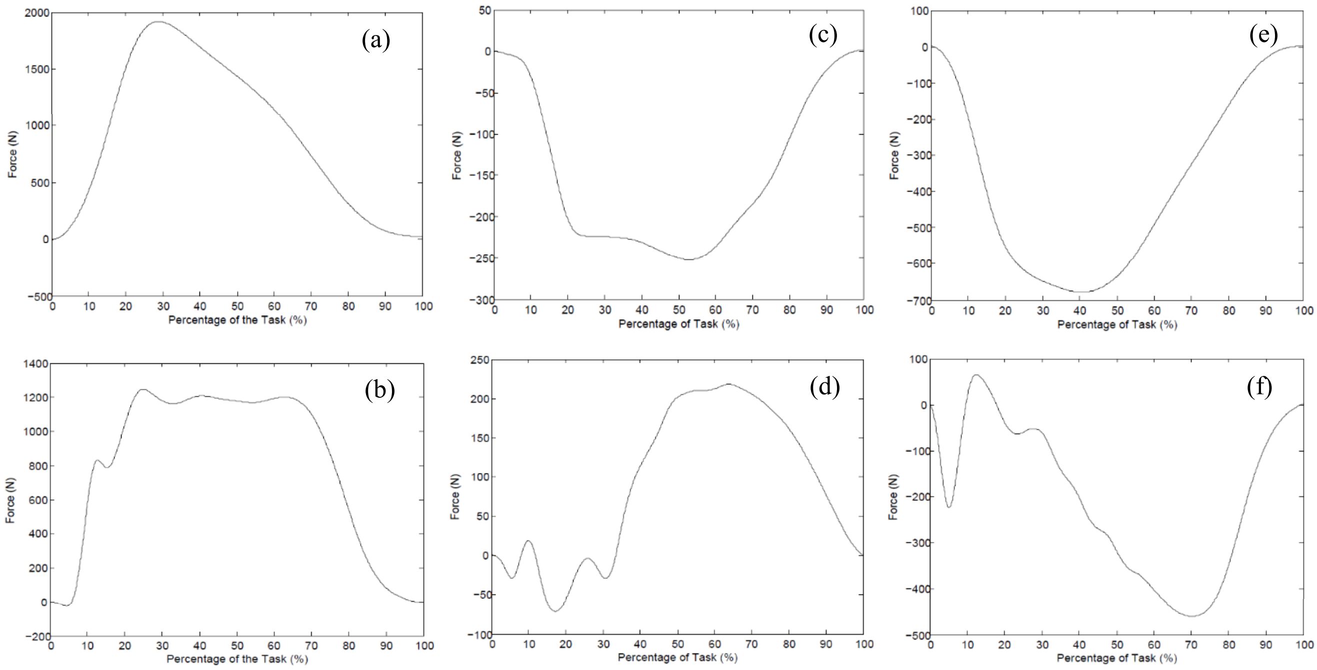

Fig. 10. Force evolutions for both feet strikes: (a) vertical force for back foot strike; (b) vertical force for front foot strike; (c) medial/lateral force for back foot strike; (d) medial/lateral force for front foot strike; (e) anterior/posterior force for back foot strike; (f) anterior/posterior force for front foot strike

anterior/posterior component is, for the back foot, 703 N (SD = 18) or 0.78 BW (SD = 0.02), while for the front foot is 462 N (SD = 28), or 0.51 BW (SD = 0.03).

3.2. Tackle effects on shoulder's physiology

Arm rotations before tackling

The isokinetic parameters recorded by the BIODEX® for the arm rotations before tackling are presented in Table 1, while the torque evolution during trials is described in Fig. 11a. The results show that the internal arm rotations have a greater strength capability (higher peak torques), despite being slower and inducing less fatigue on the athlete.

Regarding sEMG results, the three heads of the trapezius muscle are mainly active during external rotations. While for external arm rotations the peak activity and electrical impulse is, for the lower, middle and upper trapezius, respectively, 68.12% MIVC (SD = 12.31) and 0.42 V·s (SD = 0.1), 92.79% MIVC (SD = 12.08) and 0.41 V·s (SD = 0.02) and 51.47% MIVC (SD = 8.22) and 0.29 V·s (SD = 0.05), for internal arm rotations the results are: 5.30% MIVC (SD = 4.53) and 0.02 V·s (SD = 0.003), 25.63% MIVC (SD = 4.75) and 0.04 V·s (SD = 0.007) and 25.02% MIVC (SD = 1.79) and 0.07 V·s (SD = 0.02).

With the exception of the anterior portion of the deltoid, this muscle is broadly active during all ranges of rotation (internal and external). The peak activity of the middle deltoid is, for the external rotations, 59.90% MIVC (SD = 8.67) and 43.48% MIVC (SD = 8.94) for the internal configuration. As for the posterior portion, its peak activity is, for the external rotations, 74.72% MIVC (SD = 11.61) and 37.13% MIVC (SD = 7.88) for the internal rotations. Contrary to what would be expected, the anterior deltoid verifies its peak activity during external arm rotations (42.54% MIVC (SD = 15.74), while during internal arm rotations the portion is nearly inactive (3.08% MIVC (SD = 1.72)).

The latissimus dorsi is mainly active during internal rotations (peak activity is 61.27% (SD = 19.47), as expected, and as for the pectoralis major there are no relevant results in this phase, since the EMG signal was under the influence of motion artifacts.

Arm rotations after tackling

The results from the BIODEX® for the arm rotations after tackling are described in Table 1. It is important to bear in mind that, after performing multiple tackles, the athlete's peak torques for this particular arm movement change (for internal rotations the peak torque increases while for external rotations it decreases) and the time parameters increase. Figure 11b represents the torque evolution for the trials after the multiple impacts.

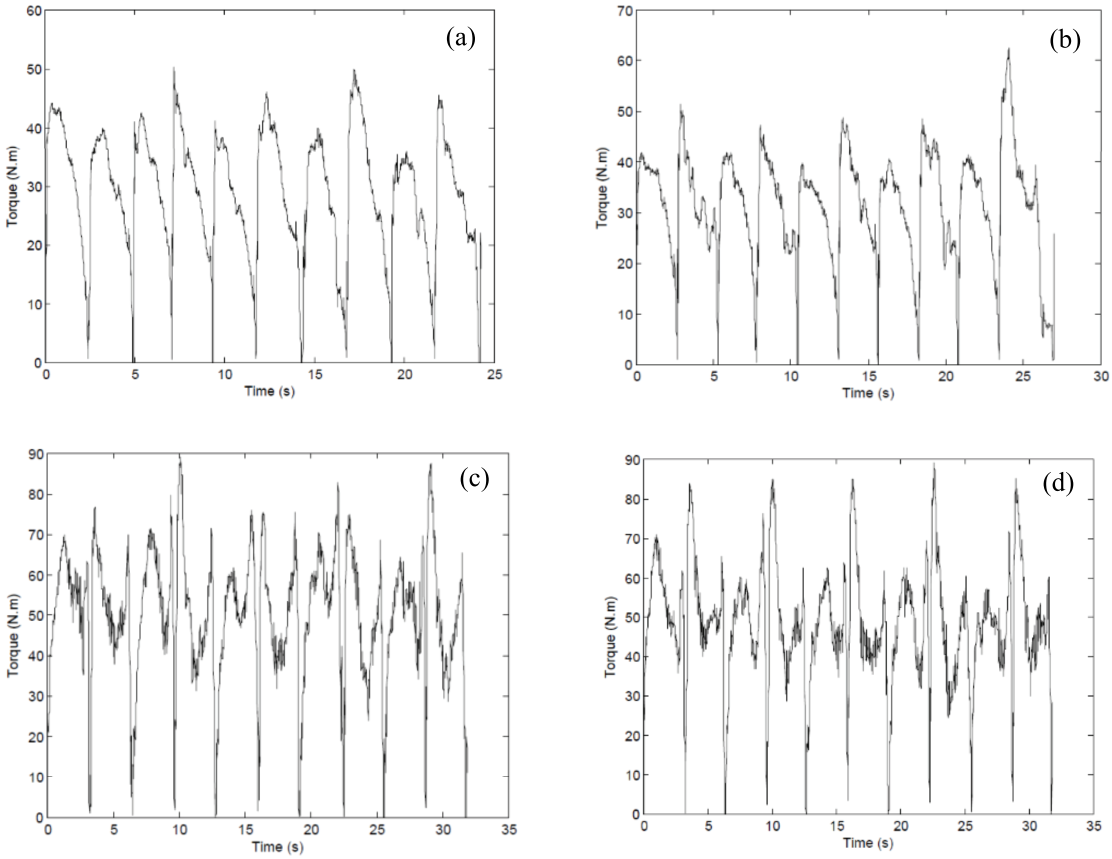

Fig. 11. Torque evolutions for: (a) arm rotations before tackling; (b) arm rotations after tackling; (c) arm abduction/adduction before tackling; (d) arm abduction/adduction after tackling

Table 1. BIODEX® results for arm rotations, before and after tackling

	BIODEX® Results Before Tackling			BIODEX® Results After Tackling	
	External Rotations	Internal Rotations		External Rotations	Internal Rotations
Peak Torque	44.1 N.m	49.3 N.m	Peak Torque	41.5 N.m	61.4 N.m
Average Peak Torque	40 N.m	45.5 N.m	Average Peak Torque	40.7 N.m	50.6 N.m
Time to Peak	0.34 s	0.4 s	Time to Peak	0.8 s	0.56 s
Acceleration	0.05 s	0.06 s	Acceleration	0.05 s	0.06 s
Deceleration	0.19 s	0.3 s	Deceleration	0.1 s	1.15 s
Fatigue	30.5 %	20.5 %	Fatigue	18 %	20 %
Average Power	28.8 W	30.5 W	Average Power	31 W	32.5 W

As for the electromyographic activity of the trapezius, it is possible to assume that its activity is approximately constant before and after tackling: while the lower trapezius increases its activity (peak activity is 98.21% MIVC (SD = 13.14) and the electrical impulse is 0.66 V·s (SD = 0.06)), the middle trapezius decreases (peak activity is 76.06% MIVC (SD = 7.99) and the electrical impulse is 0.39 V·s (0.01)).

For the deltoid, the electromyographic activity increases across all muscular portions, especially for the anterior part, during both internal and external rotations. For the posterior deltoid the peak activity and impulse are, during external rotations, 90.08 % MIVC (SD = 15.3) and 0.42 V·s (SD = 0.05). For the internal rotations the peak activity is 52.57% MIVC (SD = 12.37) and the impulse is 0.19 V·s (SD = 0.05). In terms of the middle deltoid, its peak activity for the external rotations after the tackles is 67.16% MIVC (SD = 12.77) and the impulse is 0.20 V·s (SD = 0.05). For the internal rotations, the maximum activity and impulse are, respectively, 60.30% MIVC (SD = 13.09) and 0.14 V·s (SD = 0.04). On the other hand, the anterior deltoid has, for the external rotations, 47.27% MIVC (SD = 9.82) and 0.33 V·s (SD = 0.08) as maximum activity and impulse, respectively, and 10.79% MIVC (SD = 4.66) and 0.02 V·s (SD = 0.008), for the internal rotations.

With regard to the latissimus dorsi, there is an increase of its electromyographic activity, particularly during internal rotations. While for internal rotations the peak activity is 83.00% MIVC (SD = 30.29), for external rotations it is 14.81% MIVC (SD = 2.90).

Arm abduction/adduction before tackling

Generically speaking, the adduction of the arm has greater strength capability when compared with abduction, is faster but also less effective. These evidences are supported by the results from Table 2. Figure 11c shows the torque evolution for arm abduction/ adduction before tackling.

The sEMG parameters for the three heads of the trapezius show that the muscle is primarily active during arm abduction, having its peak activity in the intermediate amplitudes of motion. While for arm abduction the peak activity and electrical impulse of the three heads of the trapezius (lower, middle and upper) are, respectively, 64.06% MIVC (SD = 6.86) and 0.53 V·s (SD = 0.03), 63.88% MIVC (SD = 6.93) and 0.42 V·s (SD = 0.03) and 89.83% MIVC (SD = 15.00), with 0.74 V·s (SD = 0.05), for arm adduction the results are 23.73% MIVC (SD = 3.35) and 0.09 V·s (SD = 0.01), 45.62% MIVC (SD = 5.33) and 0.12 V·s (SD = 0.01) and 10.40% MIVC (SD = 9.44), with 0.02 V·s (SD = 0.007).

Results also show that posterior and middle deltoid are mainly abductors, since their peak activity and electrical impulse are higher during abduction (48.95% MIVC (SD = 8.94) vs. 21.77% MIVC (SD = 5.26), for posterior deltoid; 58.63% MIVC (SD = 3.05) vs. 12.24% MIVC (SD = 3.35), for middle deltoid; 0.17 V·s (SD = 0.06) vs. 0.06 (SD = 0.01), for posterior deltoid; 0.32 V·s (SD = 0.004) vs. 0.02 V·s (SD = 0.001), for middle deltoid).

The clavicular portion of the pectoralis major is mainly abductor (peak activity during abduction is 62.43% MIVC (SD = 3.03) and 5.56% MIVC (SD = 2.11) during adduction), while the latissimus dorsi is adductor.

Arm abduction/adduction after tackling

After the set of tackles, the athlete's strength capability is compromised during arm abduction, since peak torque and average peak torque are lower than the values recorded before tackling (Table 2). Despite that, there are no relevant differences in the abduction's time parameters and on arm adduction general parameters (Table 2). Figure 11d represents the torque evolution during arm abduction/adduction after the tackles.

The electromyographic activity of the three heads of the trapezius decreases after the impacts, especially during abduction. Thus, in terms of peak activity and electrical impulse, the lower, middle and upper trapezius admit, respectively: 57.76% MIVC (SD = 3.91) and 0.55 V·s (SD = 0.06); 48.35% MIVC (SD = 5.05) and 0.32 V·s (SD = 0.03); 76.85% MIVC (SD = 6.86) and 0.70 V·s (SD = 0.02). The activity of the trapezius during adduction remains approximately unaffected.

For the deltoid, the middle portion does not suffer any change on its activity, while the anterior and posterior portions verify a muscular synergy during abduction: the posterior portion decreases its activity (peak activity is 40.83% MIVC (SD = 2.56) and electrical impulse is 0.11 V·s (SD = 0.01)) and the anterior deltoid increases its activity (qualitative comparison since the sEMG before tackles is affected by motion artifacts). The activity of this muscle during adduction, like the trapezius, remains approximately unaffected.

Table 2. BIODEX® results for arm abduction/adduction, before and after tackling

	BIODEX® Results Before Tackling			BIODEX® Results After Tackling	
	Abduction	Adduction		Abduction	Adduction
Peak Torque	80.4 N.m	87.9 N.m	Peak Torque	73.4 N.m	87.9 N.m
Average Peak Torque	73.8 N.m	79.4 N.m	Average Peak Torque	68.5 N.m	84.3 N.m
Time to Peak	2.83 s	0.42 s	Time to Peak	2.86 s	0.33 s
Acceleration	0.12 s	0.08 s	Acceleration	0.09 s	0.07 s
Deceleration	0.49 s	0.39 s	Deceleration	0.35 s	0.52 s
Fatigue	7.4 %	12.9 %	Fatigue	10.4 %	18.4 %
Average Power	50 W	48.4 W	Average Power	68.5 W	49.3 W

There is also a decrease in the maximum electromyographic activity related with the clavicular portion of the pectoralis major, during abduction, (55.58% MIVC (SD = 1.77), and 0.45 V·s (SD = 0.03) for electrical impulse), while as for the latissimus dorsi, the electromyographic parameters remained unchanged.

4. Discussion

4.1. Biomechanics of a tackle event

According to the results obtained from the modified pressure sensors matrices, the anterosuperior region of the shoulder complex is a critical area during tackles, since it is where the highest pressure values are experienced. By analysing the 3D pressure distribution at the instant of the maximum impact force (Fig. 8), it is possible to conclude that the clavicle, scapula and the trapezius muscle are the most affected anatomic structures – clavicle and scapula's spine have less muscular reinforcement, leading to a higher risk of fracture.

The pressure results also show that the acromioclavicular joint area is under particular stress during tackles, supporting the high rate of acromioclavicular injuries during rugby games [8]–[9]. This conclusion is consistent with Pain's results [18] which, despite not being able to fully correlate the pressure distribution area with the shoulder complex structures, also define the acromioclavicular joint as a critical region during tackles.

The glenohumeral joint may also be affected by the tackle impact forces, due to its proximity with the highest values of the pressure distribution. In fact, the new found critical areas of the shoulder, allied with the typical tackle mechanism (crouched position with the arms 90° abducted and fully extended), justify the arising of anterior/posterior forces, during impact, which compromise the biomechanics of the glenohumeral joint and increase the risk of shoulder dislocation [9].

In terms of the impact force on the athlete's shoulder (Fig. 9) its evolution is consistent with a high energy impact situation. Both force evolution and average peak force value are similar to the results obtained by Pain [18], since both experimental procedure and measurement equipment are similar (Table 3).

On the other hand there is a significant difference regarding the data collected by Usman [21], especially when the information is narrowed to forward athletes. This fluctuation is explained by the differences between the two experimental procedures and the selected measurement equipment. Thus, while for this particular case the tackles were performed against a shield, which turns the force values a function of the resistance imposed by the holder, in Usman's study the impacts were made against a tackle bag supported by a wall. Moreover, the run-up distance was not rigidly controlled in either study.

For the athlete's feet strikes, as it was previously said, the vertical force of each foot plays a key role, since its evolution and peak value allow evaluating the foot strike pattern and speed, respectively. Therefore, we can conclude that the athlete's back foot strike was performed at a running/jogging speed (peak force values comprised between 1.75 BW; 2.32 BW), while the front foot strike was performed at a walking speed (peak force values comprised between 1.28 BW; 1.57 BW [13], [17]. On the other hand the differences between the force evolution allow the conclusion that the left (back) foot strike has a *front-foot strike pattern* and the right (front) foot has a *rear-foot strike pattern*.

Those differences between successive footsteps imply that the athlete tends to slow down right before the impact, attaining a more stable position by changing the foot strike pattern. Thus, the effectiveness of the tackle is increased: the strike from the right (and front) foot has a higher contact time with the floor, maximizing the mechanical impulse generated by the respective leg while decreasing the peak force [17].

The medial/lateral force component is similar for both feet, highlighting its relationship with the athlete's trajectory during tackles. For this particular case, the direction of the force component is consistent with the needed centripetal force for executing a curvilinear trajectory (Fig. 3), while on other studies its value is of approximately zero for both feet

Table 3. Impact force values from different experimental studies

	Comparison of experimental studies		
	Maximum Force (N)	Maximum Force (BW)	Time to Peak (s)
Present Study	1279.02 (±114)	1.4 (±0.1)	0.05 (±0.02)
Pain et al. 2008	1283 (±608)	1.53 (±0.6)	0.082
Usman et al. 2011	1708 (±759)	2.00 (±0.9)	

(measurements performed along a rectilinear trajectory) [1].

There is also an increase in the peak value of the anterior/posterior force component, for the athlete's front foot, when compared to the values from running/walking studies [1], [17]. This difference may be related to athlete's intuition for increasing its mechanical impulse by planting the tiptoe on the floor – hence the athlete overcomes the inertia of the obstacle and tackles in a more effective way.

Despite the conclusions later mentioned, there are some limitations, concerning the present phase of the case study that compromise the results: (a) the modified pressure sensors matrix did not adapt effectively to the shoulder's curvatures, creating pre-stressed regions before the impact; (b) the calculation of the shoulder's impact force during a tackle was performed using the pressure data from the modified Teckscan® matrix; (c) tackles were performed against a shield, rather than an opponent, in a controlled environment.

4.2. Tackle effects on shoulder's physiology

Arm rotations

Regarding the isokinetic parameters for arm rotations before tackling (table 1), and comparing them with the data collected by Shklar [19] (where the subjects were civilians with no medical background on shoulder's pathologies), it is possible to clearly identify a difference between peak torque values. Not only are the torque parameters higher for the current case study, but also is the difference of peak values from complementary movements (external and internal rotations) smaller. These results show that the physical condition of rugby athletes grants them higher strength capability and greater muscle efficiency.

As for the sEMG results before the shoulder impacts, it is important to highlight the high electromiographic activity of the trapezius (especially during external rotations) when compared to the results achieved by Heuberer [11] (arm movements were performed without any resistance). This suggests that the muscular activity and pattern rely on both movement's intensity and configuration (reference position) [5] – the high intensity of the rotations and the 90° abducted position led to an increase of the trapezius (scapula rotator) activity.

The activity of the deltoid also supports the previous conclusion: while the posterior and middle portions verify an expected level of activity, the anterior deltoid has a peak activity higher than the values recorded by Heuberer [11].

After performing multiple tackles, the athlete's strength capability decreases during external rotations and increases during internal rotations (Table 1). As for the time parameters, they increase for both complementary movements. These variations may be justified by two different hypotheses: auxiliary muscles compensate damages inflicted on the main muscular structures, granting the athlete the same strength capability but, at the same time compromising the efficiency of the arm movement; or the multiple impacts affect, at first sight, the neuromuscular system, due to cumulative micro-damages on the muscular structures, which decreases the response time of the muscles during arm movements – this last hypothesis was developed on previous studies [10], [16].

By analysing the sEMG results of the deltoid and latissimus dorsi after the impacts, it is clear that the first hypothesis is more reliable. The activity of the deltoid and latissimus dorsi increases after the consecutive impacts, which may be related to a compensation effect of damages on the main rotators – muscular structures that, despite not being superficial, are approximately positioned in the critical region of the shoulder during tackles (identified in the first phase of the present case study). Having in mind this hypothesis, injuries on the rotators may compromise the dynamic stability of the glenohumeral joint, since most of them are part of the rotator cuff – which lead, in the long-term, to instability and shoulder dislocations.

The trapezius' electromiographic activity remains approximately constant, even after tackling, due to a synergy between its middle and low portions.

Arm abductions/adductions

The BIODEX® results for arm abductions/adductions before tackling are in accordance with the conclusions concerning arm rotations (Table 2). Since the isokinetic parameters are higher than those recorded by Shklar [19], and the difference between peak torque values from complementary movements (abduction/adduction) is smaller – athletes' physical condition increases their strength capability and muscular efficiency.

Concerning the sEMG results before the impacts, the trapezius is mostly active during arm abduction, which supports the scapulohumeral rhythm concept. The three heads of this muscle experience their peak activity during the intermediate amplitudes of abduction, promoting a rotational movement of the scapula that avoids any anatomical conflict with the humerus – in accordance with Wickham's results [23]. The upper head experiences the higher peak activity, implying that it is one of the most important structures for the effectiveness of the scapulohumeral rhythm. On the other hand, the decreasing activity rate is smaller for the middle trapezius, suggesting that this muscle is primarily responsible for returning the scapula to its original position (during the early stages of adduction).

Nevertheless, the sEMG results for the deltoid muscle are higher than the values reported by other studies, supporting the idea that the movements' intensity and configuration have an important role on the arm muscular activity and pattern [5], [23].

There are also differences between the measured activity of the pectoralis major and the expected results. Despite being considered an adductor, this muscle was mainly active during abductions, which implies a synergy between its two muscular portions: while the clavicular portion acts as an abductor, the costal portion also acts as an adductor [23].

After the tackles, the athlete's strength capability during abductions decreases (Table 2). Since the electrical activity of the deltoid is approximately the same, and a slight decrease of the pectoralis major's activity was registered, it is safe to assume that the decrease of the torque parameters may be due to damages inflicted on the supraspinatus muscle (which, along with the middle deltoid, is one of the main abductors). Those damages compromise the shoulder's stability, increasing the risk of dislocation.

It is also important to bear in mind the general decrease of the trapezius' activity during abductions after impacts. As this muscle is responsible for the effectiveness of the scapulohumeral rhythm, a decrease of its activity leads to inaccurate scapula position that, in the long-term, increases the risk of anatomical conflicts (e.g. subacromial conflict).

Despite the conclusions mentioned below, there are some limitations, concerning the present phase of the case study, that compromise the results: (a) Some sEMG signals had motion artifacts and other types of noise which made them difficult to analyse; (b) In some cases the MIVC tests proved to be infeasible since some muscles achieved activity values higher than 100%; (c) Athlete's warm-up and breaking times were not rigidly controlled.

5. Conclusions

To sum up, it was possible to identify a set of different characteristics related to a union rugby tackle that may affect the equilibrium of the shoulder complex:

(1) The anterosuperior region of the shoulder experiences the highest pressure values (100 kPa; 200 kPa). For that reason the clavicle, scapula, trapezius and acromioclavicular joint have a higher risk of injury during tackles;
(2) The athlete, on the verge of impact, decreases his speed and changes his foot strike pattern, increasing the mechanical impulse and stability, while decreasing the strike force;
(3) BIODEX® results showed that the athlete's physical condition is important for strength capability and movements' efficiency. On top of that the BIODEX® results along with the sEMG data prove that successive tackle events damage the rotator cuff muscles and the trapezius;
(4) A decrease of the rotator cuff efficiency leads to shoulder's instability and dislocations. As for the trapezius, the decrease of its activity jeopardizes the scapulohumeral rhythm, enhancing the risk of anatomical impingement;
(5) The results were collected using a small sample (single athlete). Thus, in order to evaluate the authenticity of the present conclusions a larger sample is required.

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References

[1] BARELA A.M., FREITAS P.B., CELESTINO M.L., CAMARGO M.R., BARELA J.A., *Ground reaction forces during level ground walking with body weight unloading*, Braz. J. Phys. Ther., 2014, 18(6). DOI: 10.1590/bjpt-rbf.2014.0058.

[2] BARTLETT R., *Introduction to Sports Biomechanics*, Routledge, 2007.

[3] BOETTCHER C.E., GINN K.A., CATHERS I., *Standard maximum isometric voluntary contraction tests for normalizing shoulder muscle EMG*, J. Ortho. Res., 2008, 26(12), DOI: 10.1002/jor.20675.

[4] CARTUCHO A., ESPERGUEIRA-MENDES J., *O Ombro*, Lidel – Edições Técnicas, 2009.

[5] DARK A., GINN K.A., HALAKI M., *Shoulder muscle recruitment patterns during commonly used rotator cuff exercises: an electromyographic study*, Phys. Ther., 2007, 87(8), DOI: 10.2522/ptj.20060068.

[6] DE LUCA C.J., GILMORE L.D., KUZNETSOV M., ROY S.H., *Filtering the surface EMG signal: Movement artifact and baseline noise contamination*, J. Biomech., 2010, 43(8), DOI: 10.1016/j.jbiomech.2010.01.027.

[7] GANTER N., WITTE K., ELDELMANN-NUSSER J., HELLER M., SCHWAB K., WITTE H., *Spectral parameters of surface electromyography and performance in swim bench exercises during the training of elite and junior swimmers*, Eur. J. Sport Sci., 2007, 7(3), DOI: 10.1080/17461390701643000.

[8] HEADEY J., BROOKS J.H.M., KEMP S.P.T., *The Epidemiology of Shoulder Injuries in English Professional Rugby Union*, Am. J. Sport Med., 2007, 35(9), DOI: 10.1177/0363546507300691.

[9] HELGESON K., STONEMAN P., *Shoulder injuries in rugby players: Mechanisms, examination, and rehabilitation*, Phys. Ther. Sport, 2014, 15(4), DOI: 10.1016/j.ptsp.2014.06.001.

[10] HERRINGTON L., HORSLEY I., WHITAKER L., ROLF C., *Does a tackling task effect shoulder joint position sense in rugby players?*, Phys. Ther. Sport, 2008, 9(2), DOI: 10.1016/j.ptsp.2008.01.001.

[11] HEUBERER P., KRANZL A., LAKY B., ANDERL W., WURNING C., *Electromyographic analysis: shoulder muscle activity revisited*, Arch. Orthop. Traum. Su., 2015, 135(4), DOI: 10.1007/s00402-015-2180-3.

[12] HUROV J., *Anatomy and Mechanics of the Shoulder: Review of Current Concepts*, J. Hand Ther., 2009, 22(4), DOI: 10.1016/j.jht.2009.05.002.

[13] KELLER T., WEISBERGER A.M., RAY J.L., HASAN S.S., SHIAVI R.G., SPENGLER D.M., *Relationship between vertical ground reaction force and speed during walking, slow jogging, and running*, Clin. Biomech., 1996, 11(5), DOI: 10.1016/0268-0033(95)00068-2.

[14] LABRIOLA J.E., LEE T.Q., DEBSKI R.E., MCMAHON P.J., *Stability and instability of the glenohumeral joint: The role of shoulder muscles*, J. Shoulder Elb. Surg., 2005, 14(1), DOI: 10.1016/j.jse.2004.09.014.

[15] MESKERS C.G.M., GROOT J.H., ARWERT H.J., ROZENDAAL L.A., ROZING P.M., *Reliability of force direction dependent EMG parameters of shoulder muscles for clinical measurements*, Clin. Biomech., 2004, 19(9), DOI: 10.1016/j.clinbiomech.2004.05.012.

[16] MORGAN R., HERRINGTON L., *The effect of tackling on shoulder joint positioning sense in semi-professional rugby players*, Phys. Ther. Sport, 2014, 15(3), DOI: 10.1016/j.ptsp.2013.10.003.

[17] MUNRO C.F., MILLER D.I., FUGLEVAND A.J., *Ground reaction forces in running: a re-examination*, J. Biomech., 1987, 20(2), DOI: 10.1016/0268-0033(87)90014-3.

[18] PAIN M.T.G., TSUI F., COVE S., *In vivo determination of the effect of shoulder pads on tackling forces in rugby*, J. Sport Sci., 2008, 26(8), DOI: 10.1080/02640410801910319.

[19] SHKLAR A., DVIR Z., *Isokinetic strength relationships in shoulder muscles*, Clin. Biomech., 1995, 10(7), DOI: 10.1016/0268-0033(95)00007-8.

[20] SUNDARAM A., BOKOR D.J., DAVIDSON A.S., *Rugby Union on-field position and its relationship to shoulder injury leading to anterior reconstruction for instability*, J. Sci. Med. Sport, 2011, 14(2), DOI: 10.1016/j.jsams.2010.08.005.

[21] USMAN J., MCINTOSH A.S., FRÉCHÈDE B., *An investigation of shoulder forces in active shoulder tackles in rugby union football*, J. Sci. Med. Sport, 2011, 14(6), DOI: 10.1016/j.jsams.2011.05.006.

[22] VEEGER H.E.J., VAN DER HELM F.C.T., *Shoulder function: The perfect compromise between mobility and stability*, J. Biomech., 2007, 40(10), DOI: 10.1016/j.jbiomech.2006.10.016.

[23] WICKHAM J., PIZZARI T., STANSFELD K., BURNSIDE A., WATSON L., *Quantifying "normal" shoulder muscle activity during abduction*, J. Electromyogr. Kines., 2010, 20(2), DOI: 10.1016/j.jelekin.2009.06.004.

[24] WILK K.E., REINOLD M.M., ANDREWS J.R., *The athlete's shoulder*, Elsevier, Inc., 2009.