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Title

The influence of playing level on the biomechanical demands experienced by rugby union forwards during machine scrummaging.

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The influence of playing level on forces in machine scrummaging.

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ABSTRACT

This study investigated machine scrummaging at different playing levels in rugby union and analysed kinetic factors that might influence performance and injury risk.

Thirty-four forward packs from six different playing levels scrummaged against an instrumented scrum machine under real environmental conditions. Applied forces were measured in three orthogonal directions.

The peak (SD) of the overall compression forces during engagement ranged between 16.5 (1.4) kN (International-Elite) and 8.7 (0.1) kN (Women), while sustained compression forces spanned between 8.3 (1.0) kN (International) and 4.8 (0.5) kN (Women). The peak of the overall vertical force during the initial engagement phase was between -3.9 (0.7) kN (Elite) and -2.0 (1.0) kN (School), and the range of lateral forces was between 1.8 (0.3) kN (International) and 1.1 (0.3) kN (School). Forces measured across all playing levels, particularly during initial engagement, were generally higher than those measured in the most commonly cited previous studies. This increase may be due to a combination of changes in modern scrummaging technique, changes in players' anthropometrics, and experimental conditions that better respect ecological validity.

The magnitude of the measured forces is in the range of values that studies on cadaveric specimens have indicated as potentially hazardous for (chronic) spine injuries.

INTRODUCTION

The scrum in rugby union is a means of restarting play following a minor infringement or stoppage (IRB 2012), whereby eight players (i.e. the “forward pack”) from each team bind in three rows and engage with the opposition pack to contest the ball under the direction of the referee. From a biomechanical perspective the scrum is a complex event, in which technique and strength are equally fundamental in achieving optimal performance. Scrummaging involves a high initial impact at the engagement, followed by an intense sustained push after the two front rows have bound together (Milburn 1990; Preatoni et al. 2012). These pushing actions, coupled with forces and movements acting in all the three planes of motion generate intense physical demands on the forwards’ musculo-skeletal structures and therefore deserve special attention from an injury prevention perspective.

Injuries from scrum events account for 6-8% of the overall injuries in rugby union (Brooks et al. 2005; Targett 1998), and scrummaging has been associated with approximately 40% of catastrophic rugby injuries that typically involve the spinal cord (Quarrie et al. 2002). The occasional maximal and the repetitive submaximal stresses acting on the player’s anatomical structures and on the spine in particular may be a factor for an increased risk of acute and chronic injuries. Overuse pathologies such as anatomical abnormalities (Berge et al. 1999; Castinel et al. 2010) and reduced mobility (Lark & McCarthy 2007; Scher 1990) of the spine, or impaired proprioception (Pinsault et al. 2010; Scher 1990), have been identified in older rugby forwards and may emerge in later years as a consequence of repeated micro-traumas from scrummaging.

Little quantitative information is available regarding the forces and motion involved in modern rugby scrummaging, especially since professionalism was introduced in 1995. A small number of studies show that forces of a considerable magnitude may be generated during the engagement phase (Du Toit et al. 2004; Milburn 1990; Quarrie & Wilson 2000; Rodano & Tosoni 1992). However, most of the research is now rather dated and/or has limited applicability due in various proportions to lack of ecological validity (e.g. scrummaging against rigid metal frames), measurement issues (e.g. sampling rates, players only analysed individually, small sample sizes), and the changes in engagement techniques and playing styles over the years. A thorough description of the differences in scrum biomechanics at different playing levels is also missing.

Therefore, the aim of this research was to: (1) describe the forces developed during machine scrummaging as a factor of playing level; (2) evaluate whether the magnitude and characteristics of the force load on players may represent an issue for potential injury.

MATERIALS AND METHODS

Study design

This is a cross-sectional study in which repeated machine scrummaging trials were performed to assess the characteristics of the forces exerted by rugby forward packs, and to compare these forces at different playing levels.

Participants

Thirty-four forward packs were grouped into six pre-determined categories (International, Elite, Community, Academy, Women and School – Table 1) according to their playing level. Before participation each player provided written informed consent. Ethical approval was obtained by the institutional ethics committee of the University of Bath.

**** Table 1 here ****

Data Collection

Following a coach-directed warm-up including submaximal engagements, each team performed between 4-8 machine scrummaging trials. Recovery intervals (1-2 min) were included between repetitions to avoid fatigue. Scrums were performed outdoors, on natural turf, against a scrum machine (Dictator, Rhino Rugby, UK). The experiment was devised such that environmental conditions would mimic as effectively as possible actual scrummaging conditions (Preatoni et al. 2012) (Figure 1).

**** Figure 1 here ****

Instrumentation and Data Processing

Each of the four pusher arms of the scrum machine was instrumented with strain gauge force sensors to measure compression (F_y>0 for pushing forces), lateral (F_x>0 for forces directed to the right) and vertical bending (F_z>0 for forces directed upward) forces which had been laboratory calibrated (Preatoni et al. 2012). During data collection the scrum machine was fixed to the ground so that no appreciable movement of the whole machine could be registered and the assumption of static condition could be respected. A bespoke control and acquisition system (cRIO-9024, National Instruments, USA) programmed (Labview 2010, National Instruments, USA) to work with deterministic timing was used to synchronously: (1) simulate the referee's call as during a real scrummage by delivering consistently timed "crouch-touch-pause-engage" audio commands (duration of full sequence = 5.00 s); and (2) excite strain gauge bridges and collect their signals at a frequency of 500 Hz. Custom-written software (Matlab R2010b, MathWorks, USA) was used to filter data by applying an adaptive low-pass zero-lag 4th-order Butterworth filter (Erer 2007; Preatoni et al. 2012) with a cutoff frequency between 4 and 80 Hz and to calculate a set of 195 parameters for each scrum repetition. Parameters were selected with the aim of describing the kinetics of the pack-machine interaction across the subsequent phases of the push and its possible relation with performance and/or injury factors. Shock absorption (SABS) was defined as the interval between the instant of first contact of the forward pack with the pusher arms until 1 s after engagement; sustained push (SPSH) extended from the end of SABS for 1 s. The parameters included (Table 2) maxima and minima of force, impulses, average sustained pushes, and relative timing. Figure 2 shows typical force patterns with annotation of the principal calculated variables. In this paper, the overall forces (i.e. the sum of the forces on the four pusher arms) will be considered.

**** Figure 2 here ****

Statistics

Average measures from individual teams were grouped according to playing level and descriptive statistics were reported. One-way ANOVA (with playing level as the between group factor) and Bonferroni post-hoc analysis were used to assess the significance ($P<0.05$) of possible differences across playing levels. Pairwise effect sizes (Cohen's d) (Cohen 1988) were also considered in addition to better depict the magnitude of effects between categories and to mitigate the possible presence of Type II error.

RESULTS

Compression Forces

Compression forces during engagement exhibited a short-duration impact peak before dropping to a minimum and rising back to a relatively consistent sustained push (Figure 2). The peak compression force during engagement ranged between 16.5 (1.4) kN (International and Elite) and 8.7 (0.1) kN (Women), while sustained compression force spanned between 8.3 (1.0) kN (International) and 4.8 (0.5) kN (Women). ANOVA showed significant effects for playing level in all variables (Table 2). Partial eta-squared was large for all the parameters and observed power always greater than 0.98. Post-hoc analysis depicted a subdivision into three main sub-groups, with results of the International and Elite categories that generally showed greater magnitudes compared to the Community and Academy teams, and with these latter playing levels achieving higher values than the Women and School packs (Table 2). For most of the measures, only the International and Elite levels were statistically different from the others. However, pairwise effect sizes (Supplement 1) supported the three-subgroup subdivision, with Cohen's *d* that were small in within-subgroup pairs (e.g. International and Elite) and very large in between-subgroups pairs (e.g. Academy and Women).

**** Table 2 here ****

When measures of compression force were normalized by the pack weight, significant differences across groups were still present for all parameters with the exception of the propulsive impulse (P=0.28). The three-step subdivision remained, but many of the statistically significant differences in the post-hoc analysis disappeared (Table 3). Peak compression stayed greater for International and Elite, but, for example, the average sustained push in the Women group was no longer less than in International and Elite. In all the measures, the pairwise effect size analysis (Supplement 2) separated the International and Elite subgroup from the other four categories, with the exception of: positive impulse, for which small effect sizes pooled together the International, Elite, Community and Academy teams, separating them from the Women and School ones; and negative impulse, for which small effects united Community to School (most reduced loss of compressive impulse) and Academy to Women (intermediate loss of compressive impulse).

**** Table 3 here ****

Lateral Forces

Patterns of lateral forces were generally less consistent than the ones of compression and vertical forces, and their magnitudes were approximately 10% of compression forces. The range of lateral forces (Table 4) evidenced significant pairwise differences ($P<0.01$) only when the International and Elite levels, 1.8 (0.3) and 1.8 (0.2) kN, respectively, were compared against School level, 1.1 (0.3) kN. Despite this, pairwise effect sizes evidenced very large differences (Supplement 3) between all the groups besides the International-Elite and the Academy-Women couplings. Average lateral force during sustained push was very close to zero, with generally a slight tendency to positive values (right direction). ANOVA reported a main effect ($P=0.03$) but no post-hoc differences emerged across groups. However, pairwise effect sizes separated the International and Elite (more intense sustained pushes to the right) from the other groups.

**** Table 4 here ****

Vertical Forces

During engagement, the negative (downward) peak of the overall vertical force was between -3.9 (0.7) kN (Elite) and -2.0 (1.0) kN (School) (Table 5), evidencing significant differences (P=0.03) only between Elite and School packs. No significant differences were reported in the average sustained vertical push, which tended to show positive (upward) values for the International and Elite categories, while was close to zero for the other playing levels. However, similar to most of the other kinetic parameters, pairwise effect sizes (Supplement 3) tended to separate the International and Elite (more intense downward force on engagement and upward forces during sustained push) from the other groups. The magnitude of vertical forces during the engagement phase were in the range of approximately 20% of compression forces.

**** Table 5 here ****

DISCUSSION

The aim of this research was to evaluate the forces generated during rugby scrummaging on a scrum machine at various playing levels and hence to gain more insight into the factors that may play a role for injury prevention and performance.

The recorded forces showed basic patterns similar to those already described in the literature (Milburn 1990), with a high compression peak at the initial engagement, followed by a drop in the force the pack is able to apply against the machine (‘rebound effect’), and by a recovery of the pushing capacity during the sustained phase (Figure 2). However, the magnitude of summed forces across the front row was considerably higher than in Milburn’s previous study for all comparative playing levels (Milburn 1990) (e.g. 16.5 vs. 8.0 kN, 8.3 vs.5.8 kN for the peak compression force and the average sustained push, respectively, in the International category), but more in line with other data referring to international youth (Retiere 2010; Rodano & Tosoni 1992) or to top grade amateur teams (Quarrie & Wilson 2000). The possible differences in force outcomes between studies may be ascribed to an improved ecological validity in collecting data and to changes in scrummaging technique and players’ anthropometrics over the last 20 years (Brooks & Kemp 2008; Quarrie & Hopkins 2007).

Since it may be expected that players of higher body mass would produce more force in absolute terms due to larger inertia effects, measures normalized to pack weight were also considered. Even after normalization the International and Elite categories generated higher maximum compression forces than all other categories. Therefore the higher level teams managed to exploit better technique and/or physical conditioning and produced a more effective action at the beginning of the engagement. However, this ability was not maintained throughout the push. The International and Elite category exhibited a greater drop in normalized compression force after the peak than the other categories, reflective of a period of sub-optimal force production and reversal of velocity, before rising back to a higher normalized sustained force than the Academy, Community and School categories. This may be the result of different approaches to the engagement phase: an aggressive style versus a more continuous style, which is in line with the ‘impulsive push’ and ‘maintenance push’ styles proposed by Rodano & Tosoni (1992).

The magnitude of sustained compression forces was approximately 50% of the magnitude of the peak compression forces during engagement. This is a larger difference than observed in previous research (Milburn 1990), where sustained forces were approximately 75% of engagement forces, and may be ascribed to relatively higher peak forces in the current data. As such, there is a suggestion that engagement forces (due to the collision-type engagement seen in modern rugby) have increased comparatively more than sustained forces over time.

Vertical force showed a negative (downwards) peak soon after engagement of the forward pack with the machine, which occurred approximately at the same time as the peak compression force. The results of the current study differ from findings of previous authors, who measured forces in the region of -1 kN (Milburn 1990; Retiere 2010) for all categories except International (Milburn 1990) who at that time produced a substantial upwards force. Whilst most recent studies (Quarrie & Wilson 2000; Retiere 2010) have noted a downward force during engagement, which is reinforced by the orientation of the front row players at engagement (shoulders below hips), the actual magnitude of vertical forces may be more influenced than the forces in other directions by the design of the scrum machine and by the position of the head (constrained or not). Within this study, magnitudes of both negative peak and sustained vertical force differentiated the International and Elite categories from the others, although there was a large amount of variability between packs within each playing level. During the sustained push International and Elite levels generated greater vertical upward forces than the other groups, for whom the vertical component was about zero. It may be argued that if the production of vertical forces transferred to live scrummaging and both packs behaved similarly, the risk of scrum collapse or disruption would increase by creating a rotational momentum on the front row opponents. However, it should also be observed that the players involved in this testing knew they were engaging against a static object and might have adjusted their engagement strategy relying on the stable opposition exerted by the scrum machine.

Lateral force patterns were more inconsistent between trials and teams and lower in intensity than in the compression and vertical directions. Even with a progressive increase of values from School to International, all categories produced a sustained lateral push directed towards the tight-head prop side, which may relate to the tactical choice of achieving counterclockwise rotation of the scrum on a team's attacking put-in to take the opposition back-row away from the direction of play and offer more security to the scrum half of the team in possession. This outcome is in opposition with Milburn (1990) who found forces directed to the left and with greater magnitudes than the average of our teams in the same category.

The development of vertical and lateral shear forces may be counter-productive for scrummaging (takes away from compression forces) and may also be a risk factor for chronic degeneration of the spine (Scher 1983) because shear forces introduce a moment of force which is not present during pure compression which would tend to induce undesirable rotation and/or bending of the spine.

Bearing in mind that machine scrummaging may have different characteristics from contested "live" scrummaging, the magnitude of the engagement and sustained forces, in combination with (i) the presence of vertical and lateral shear forces, (ii) the geometric misalignment of body segments that may be observed by video recordings, (iii) the constrained head and body segment motions, and (iv) the repeated loading to which players are subjected during training and matches, places the rugby forward in a situation which studies on cadaveric specimens have indicated has the potential to produce the repetitive sub-critical injuries that might lead to chronic pain and early degenerative changes to the cervical and lumbar spine (Adams et al. 2000; Nightingale et al. 1996; Panjabi 2006; Przybyla et al. 2007; Yoganandan et al. 1986). Analysis of front row player movements returned values for speed of engagement exceeding 3.0 m/s for higher level groups. In the context of human impacts, these velocities are relatively low if compared with, for example, motor vehicle collisions, but are not dissimilar to an athletic sprinter leaving the blocks (Bezodis et al. 2010). Previous studies of spinal injury mechanisms (Nightingale et al. 1997; Winkelstein & Myers 1997) have highlighted that cervical spine injury is possible at similar velocities (3.1 m/s) if the head is constrained from moving and external loads continue to be applied at both ends of the segment, leading to buckling mechanisms. This condition is similar to what tight rugby forwards (front row and second row) experience when scrummaging. Whilst serious low-velocity injuries are rare in the scrum and very much represent a worst case scenario, borrowing from the work of Panjabi (2006) it seems plausible that even if damage is not catastrophic or even noticeable in terms of acute injury, the repeated cycles of scrummaging with constrained body motion, high compressive forces and non-axial loading may increase the risk of chronic degeneration of the spine over a longer period of time. However, the above observations are speculative and based on a transfer of general injury-mechanism literature to the specific rugby scrum situation. Further investigations that also include a quantitative measurement of body alignment are needed to give a better evaluation of potential injury risks during rugby scrummaging.

PERSPECTIVES

The present study is the first to systematically measure scrum forces across multiple playing levels. It has thus established the force characteristics of contemporary rugby union scrummaging to illuminate the considerable demands of the activity and the loads imposed on players. The data provides a more comprehensive picture of the differences in scrummaging biomechanics related to different playing levels and benchmarks the force characteristics of current scrummaging techniques against which modified scrummaging techniques can be compared. In relating the force outputs from this study to previously available data and considering the loading environment that the rugby forward is subjected to in the scrum then actual scrummaging may include hazardous factors for chronic injury, primarily to the cervical spine.

Our findings have potential implications for: (1) team personnel (e.g. coaches, physicians, physiotherapists) and governing bodies, to provide guidance towards enhanced 'good practice' for players' health and safety; (2) providing a reference and a method for improving scrummaging technique and its monitoring; and (3) representing a basis for a more thorough understanding of the stresses acting on rugby forwards while scrummaging and of the mechanisms that cause acute and chronic injuries.

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TABLES

Table 1. Forward packs subdivision and average pack weight.

Category	Definition (# teams)	Pack Weight$^{(*)}$
International (I)	Senior international packs or full-time professional packs with >4 senior international players (6)	8749 (165)
Elite (E)	Full-time professional packs from top level of club game (6)	8523 (143)
Community (C)	Amateur packs from levels 5-7 of English community rugby (6)	8262 (325)
Academy (A)	Academy packs from full-time professional club (3) or 1st XV university packs (3)	7771 (197)
Women (W)	Senior international packs (2) or 1st XV packs from top level of club game (2)	6326 (257)
School (S)	Under 18 male packs from professional clubs (2) or amateur clubs (2) or schools competing in English National Schools U18 Cup (2)	6685 (637)

$^{(*)}$= mean (standard deviation). Weight is reported in N.

Table 2. Compression force$^{(**)}$ parameters.

Variable\Category	I	E	C	A	W	S
Peak compression $^{(†)}$	16.5 ^{c,a,w,s}	16.5 ^{c,a,w,s}	12.0 ^{i,e}	11.7 ^{i,e}	8.7 ^{i,e}	9.1 ^{i,e}
($F_{y\text{-}MAX}$)	(1.4)	(1.4)	(1.6)	(2.0)	(0.1)	(3.2)
Average sustained push $^{(†)}$	8.3 ^{c,a,w,s}	8.0 ^{c,a,w,s}	5.8 ^{i,e}	5.9 ^{i,e}	4.8 ^{i,e}	4.9 ^{i,e}
($F_{y\text{-}SPSH}$)	(1.0)	(0.7)	(0.4)	(0.8)	(0.5)	(1.3)
Drop from peak to sustained force	8.4 ^{w,s}	8.6 ^{w,s}	6.3	6.0	3.9 ^{i,e}	4.5 ^{i,e}
(Δ_1) $^{(†)}$	(0.9)	(1.4)	(1.6)	(1.6)	(0.5)	(2.3)
Rise from minimum to sustained	3.1 ^{c,a,w,s}	2.7 ^{w,s}	1.5 ^{i}	1.6 ^{i}	1.2 ^{i,e}	1.1 ^{i,e}
force (Δ_2) $^{(†)}$	(1.3)	(0.5)	(0.5)	(0.5)	(0.3)	(0.5)
Positive impulse $^{(†)}$	3.1 ^{w,s}	3.3 ^{w,s}	3.0 ^{w,s}	2.8	2.1 ^{i,e,c}	2.2 ^{i,e,c}
(I^+)	(0.3)	(0.4)	(0.8)	(0.3)	(0.1)	(0.3)
Negative impulse $^{(†)}$	-1.0 ^{s}	-1.1 ^{c,s}	-0.4 ^{e}	-0.5	-0.4	-0.3 ^{i,e}
(I^-)	(0.7)	(0.4)	(0.2)	(0.2)	(0.2)	(0.2)

$^{(**)}$ measures are the sum of the forces on the four pusher arms, and are reported as mean (standard deviation). Force units are kN. Impulse units are kN•s. Δ_1 is the drop in force from peak compression to average sustained push. Δ_2 is the rise in force from minimum compression to average sustained push. I^+ is the area under the compression force curve, calculated between the time of real engagement and the instant when the force drops down to the value of the sustained push. I^- is the area between the level of sustained push and the compression force curve, calculated between the end of the I^+ interval and the beginning of the sustained push phase. Significant differences (P<0.05) between playing levels $^{(†)}$ are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{a}= different from Academy; ^{w}= different from Women; ^{s}= different from School.

Table 3. Normalised compression force[°] parameters

Variable\Category	I	E	C	A	W	S
Peak compression [†]	1.88 [c,a,w,s] (0.15)	1.94 [c,a,w,s] (0.16)	1.45 [e,i] (0.18)	1.50 [e,i] (0.25)	1.37 [e,i] (0.07)	1.34 [e,i] (0.35)
Average sustained push [†]	0.95 [a,c,s] (0.12)	0.94 [c,s] (0.09)	0.70 [i,e] (0.04)	0.76 [i] (0.09)	0.76 (0.10)	0.72 [i,e] (0.14)
Δ_1 [†]	0.96 (0.10)	1.01 [w,s] (0.16)	0.77 (0.18)	0.77 (0.20)	0.62 [e] (0.08)	0.66 [e] (0.29)
Δ_2 [†]	0.35 [c,s] (0.15)	0.32 (0.06)	0.18 [i] (0.07)	0.20 (0.06)	0.18 (0.05)	0.17 [i] (0.07)
Positive impulse [†]	0.36 (0.03)	0.39 (0.04)	0.37 (0.09)	0.36 (0.04)	0.33 (0.01)	0.33 (0.03)
Negative impulse [†]	-0.11 (0.08)	-0.13 [c,s] (0.05)	-0.04 [e] (0.02)	-0.06 (0.03)	-0.06 (0.03)	-0.04 [e] (0.02)

[°] measures are the sum of the forces on the four pusher arms, and are reported as mean (standard deviation). Force units are adimensional. Impulse units are s. Δ_1 is the drop in force from peak compression to average sustained push. Δ_2 is the rise in force from minimum compression to average sustained push. Significant differences (P<0.05) between playing levels [†] are reported by the following convention: [i]= different from International; [e]= different from Elite; [c]= different from Community; [a]= different from Academy; [w]= different from Women; [s]= different from School.

Table 4. Lateral force(**) parameters.

Variable\Category	I	E	C	A	W	S
Range of lateral force (†) (ΔF_x)	1.8 [s] (0.3)	1.8 [s] (0.2)	1.5 (0.2)	1.3 (0.2)	1.3 (0.2)	1.1 [i,e] (0.3)
Average sustained lateral push (†) $(F_{x\text{-}SPSH})$	0.6 (0.5)	0.6 (0.4)	0.1 (0.6)	0.1 (0.3)	-0.1 (0.3)	0.1 (0.3)

(**) measures are the sum of the forces on the four pusher arms, and are reported as mean (standard deviation). Force units are kN. Significant differences (P<0.05) between playing levels (†) are reported by the following convention: [i]= different from International; [e]= different from Elite; [c]= different from Community; [a]= different from Academy; [w]= different from Women; [s]= different from School.

Table 5. Vertical force(**) parameters.

Variable\Category	I	E	C	A	W	S
Peak downward force (†)	-3.6	-3.9 ^{s}	-2.3	-2.9	-2.4	-2.0 ^{e}
(ΔF_z)	(1.4)	(0.7)	(1.1)	(1.1)	(0.7)	(1.1)
Average sustained vertical push	1.1	0.7	-0.0	0.1	0.0	0.1
($F_{z\text{-}SPSH}$)	(1.3)	(0.9)	(0.9)	(0.6)	(0.5)	(0.9)

(**) measures are the sum of the forces on the four pusher arms, and are reported as mean (standard deviation). Force units are kN. Significant differences (P<0.05) between playing levels (†) are reported by the following convention: ^{i}= different from International; ^{e}= different from Elite; ^{c}= different from Community; ^{a}= different from Academy; ^{w}= different from Women; ^{s}= different from School.

FIGURE LEGENDS

Figure 1. The experimental set-up from the top (a) and left (b) view, including the force coordinate system: x= lateral; y= compression; z= vertical.

Figure 2. Typical force patterns: (a)-(b) compression; (c) lateral; (d) vertical. Please refer to Table 2 for a description of the parameters.

FIGURES

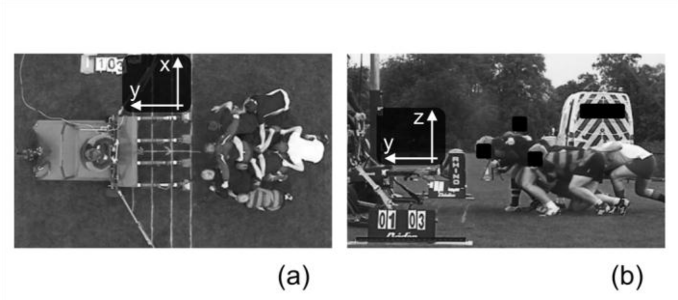

Figure 1. The experimental set-up from the top (a) and left (b) view, including the force coordinate system: x= lateral; y= compression; z= vertical.

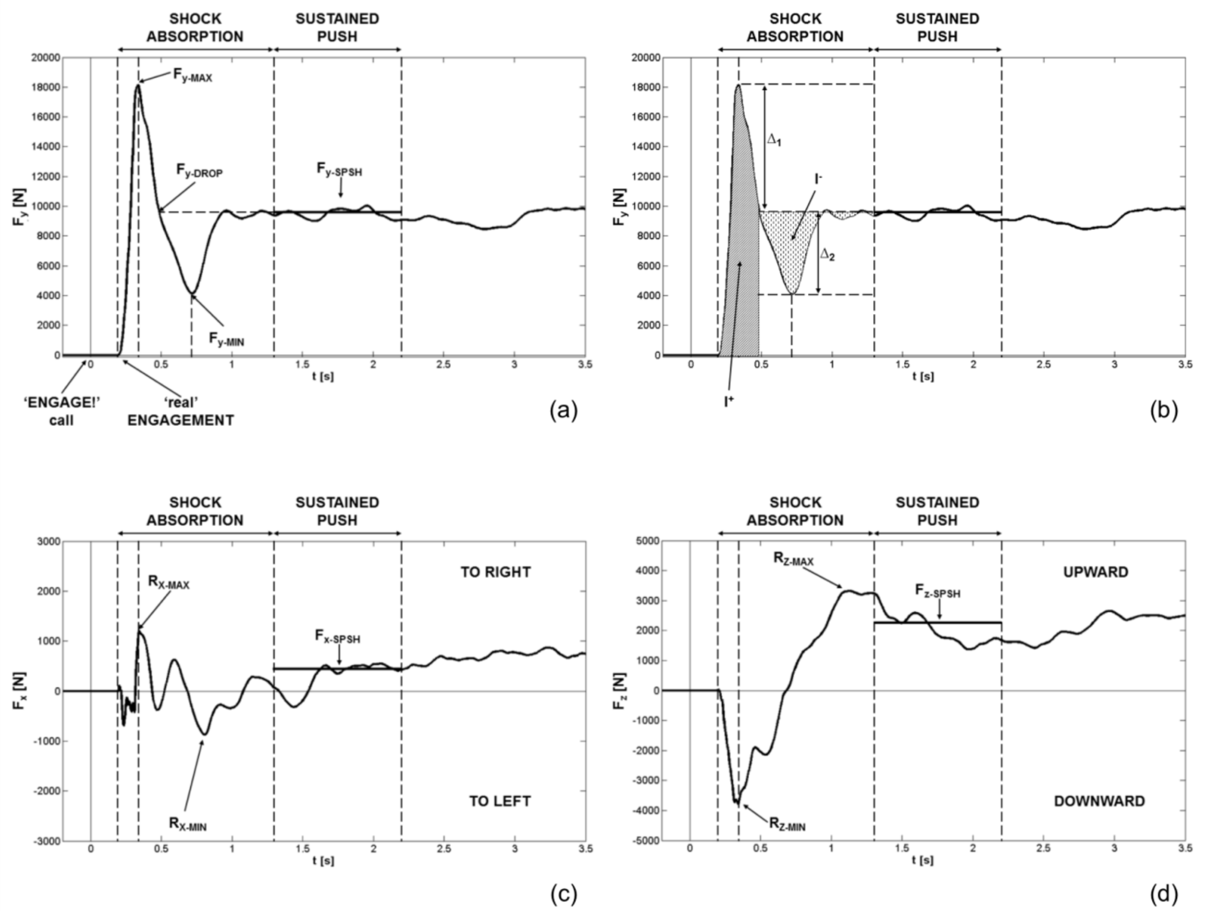

Figure 2. Typical force patterns: (a)-(b) compression; (c) lateral; (d) vertical. Please refer to Table 2 for a description of the parameters.

SUPPLEMENT

Supplement 1. Pairwise effect sizes[(#)] for compression force variables. Rows are playing level pairs (I= International, E= Elite, C= Community, A= Academy, W= Women, S= School). Columns are force parameters (please refer to Table 2 and Figure 2 for their description).

Pairs\Parameter	$F_{y\text{-}MAX}$	$F_{y\text{-}SPSH}$	Δ_1	Δ_2	I^+	I^-
I-E [(§)]	**-0.04**	**0.41**	**-0.24**	**0.44**	**-0.49**	**0.27**
I-C	3.30	3.65	1.76	1.75	**0.18**	-1.39
I-A	3.03	2.90	2.04	1.62	1.35	-1.12
I-W	8.10	4.68	6.49	2.00	4.73	-1.22
I-S	3.30	3.19	2.38	2.09	3.35	-1.66
E-C	3.32	4.05	1.69	2.73	**0.45**	-2.77
E-A	3.05	2.95	1.94	2.50	1.60	-2.29
E-W	8.09	5.46	4.54	4.09	4.03	-2.54
E-S	3.31	3.15	2.32	3.39	3.29	-3.29
C-A [(§)]	**0.18**	**-0.28**	**0.26**	**-0.29**	**0.49**	0.65
C-W	2.91	2.44	2.10	0.73	1.72	**0.21**
C-S	1.24	0.99	0.99	0.67	1.58	-0.74
A-W	2.09	1.86	1.73	1.11	3.18	**-0.48**
A-S	1.05	1.06	0.78	0.98	2.12	-1.40
W-S [(§)]	**-0.21**	**-0.09**	**-0.36**	**0.06**	**-0.39**	-1.05

[(#)] Cohen's *d*. Small: d= 0.20; medium: d= 0.50; large: d= 0.80.[16] Small effect size occurrences have been highlighted in bold. [(§)] Pairs of the same subgroup.

Supplement 2. Pairwise effect sizes(#) for normalised compression force variables. Rows are playing level pairs (I= International, E= Elite, C= Community, A= Academy, W= Women, S= School). Columns are force parameters (please refer to Table 3 and Figure 2 for their description).

Pairs\Parameter	$F_{y\text{-}MAX}$	$F_{y\text{-}SPSH}$	Δ_1	Δ_2	I^+	I^-
I-E (§)	**-0.39**	**0.14**	**-0.46**	**0.36**	-0.83	**0.32**
I-C	2.84	3.13	1.44	1.64	**-0.14**	-1.33
I-A	1.97	1.96	1.29	1.40	**0.05**	-0.98
I-W	4.46	1.91	4.19	1.52	1.33	-0.89
I-S	2.22	1.98	1.53	1.75	1.25	-1.49
E-C	3.13	3.69	1.58	2.45	**0.30**	-2.64
E-A	2.23	2.10	1.46	2.05	0.82	-2.06
E-W	4.70	2.10	3.24	2.65	1.95	-1.93
E-S	2.42	2.05	1.67	2.62	1.91	-2.92
C-A (§)	**-0.26**	-0.98	**-0.01**	**-0.48**	**0.16**	0.78
C-W	0.59	-0.93	1.06	**-0.12**	0.62	0.87
C-S	**0.43**	**-0.23**	**0.49**	**0.20**	0.71	**-0.38**
A-W	0.71	**0.05**	0.96	**0.41**	1.08	**0.06**
A-S	0.58	**0.40**	**0.48**	0.68	1.08	-1.16
W-S (§)	**0.13**	**0.34**	**-0.17**	**0.34**	**0.18**	-1.28

(#) Cohen's *d*. Small: d= 0.20; medium: d= 0.50; large: d= 0.80.[16] Small effect size occurrences have been highlighted in bold. (§) Pairs of the same subgroup.

Supplement 3. Pairwise effect sizes[(#)] for shear force variables. Rows are playing level pairs (I= International, E= Elite, C= Community, A= Academy, W= Women, S= School). Columns are force parameters (please refer to Table 4, Table 5 and Figure 2 for their description).

Pairs\Parameter	ΔF_x	$F_{x\text{-}SPSH}$	$F_{z\text{-}MIN}$	$F_{z\text{-}SPSH}$
I-E [(§)]	**0.07**	**-0.06**	**0.27**	**0.35**
I-C	0.97	1.04	-1.16	1.09
I-A	1.70	1.27	-0.69	1.04
I-W	1.80	1.92	-1.16	1.10
I-S	2.43	1.42	-1.43	0.96
E-C	1.26	1.16	-1.92	0.93
E-A	2.27	1.49	-1.28	0.87
E-W	2.57	2.29	-2.50	1.01
E-S	3.13	1.70	-2.33	0.76
C-A [(§)]	0.90	**-0.05**	0.53	**-0.18**
C-W	1.11	**0.48**	**0.13**	**-0.05**
C-S	1.83	**0.01**	**-0.29**	**-0.16**
A-W	**0.21**	0.80	**-0.49**	**0.17**
A-S	1.01	0.08	-0.83	**0.00**
W-S [(§)]	0.81	-0.84	**-0.48**	**-0.13**

[(#)] Cohen's *d*. Small: d= 0.20; medium: d= 0.50; large: d= 0.80.[16] Small effect size occurrences have been highlighted in bold. [(§)] Pairs of the same subgroup.