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An integrated measurement system for analysing impact biomechanics in the rugby scrum

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ABSTRACT

As part of a wider project investigating the biomechanics of the rugby scrum within rugby union, the focus of the present study was to design, realise and test an unobtrusive measurement system for assessing the kinematics and kinetics of rugby forwards while scrummaging on the pitch in realistic environmental conditions. Currently the study investigates one forward pack (8 players) scrummaging against an instrumented scrum machine, a training aid used widely throughout rugby. The measurement system integrates three different subsystems for: (I) measuring forces exerted by players; (II) capturing players' movements; and, (III) triggering/synchronizing all the sensors involved in I and II. Applied 3D forces were measured by strain gauge circuits attached to each pusher arm of the machine and then summed to produce the components of overall force. Multiple camera views allowed the recording and subsequent analysis of player movements, in the primary transverse (50 Hz and 200 Hz) and sagittal (50 Hz) planes of motion. A control system executed pre-recorded audio commands to players with consistent timings, sent trigger pulses to acquisition devices and collected analogue data at 500 Hz. The overall system has been applied successfully in the field to record data from rugby union forward packs across a range of playing levels and initial results confirm that the measurement system will be useful for its desired purpose to compare the biomechanics of different scrum engagement techniques.

INTRODUCTION

Competitive scrummaging is a fundamental component of rugby union. It represents both a powerful offensive skill that provides a base for launching attacks, and a defensive one that aims at disrupting the opposition possession. Given its intense physical nature and the presence of impacts, the rugby scrum may engender very high biomechanical demands on the players' musculo-skeletal structures and may thus expose rugby forwards to the risk of both acute and chronic (overuse) injuries. Epidemiological studies of rugby injury [1, 2] have shown a moderate incidence of scrum-related injuries (6-8% of all rugby injuries), but have also evidenced the potential seriousness of these occurrences. In fact, even though recent data have suggested a relative decline of scrum related serious injuries, about 40% of the catastrophic (typically spinal cord) injuries that occur in rugby are related to scrummaging [3]. Furthermore, players may appear asymptomatic while they are active, but they may experience repeated micro-trauma [4] that can contribute to the emergence of long-term pathologies of the spine, including abnormalities [5, 6], reduced mobility [7], and impaired proprioception [8].

While rugby scrums may be associated with a number of potential injury risk factors, there is currently very little quantitative data that tries to identify and describe them. There is a lack of information about the forces and motions involved in actual scrummaging, and, consequently, little objective knowledge about how performance could be optimized and injuries prevented. Quantitative

research on the rugby scrum has been occasional [9-12] and has demonstrated that high forces can be generated, particularly during the engagement phase (e.g. ~8000 N peak compression force across the front row of an International forward pack [10]). However, these findings are now limited in applicability due in various proportions to lack of ecological validity (e.g. scrummaging against rigid frames), measurement issues (e.g. sampling rates, players only analysed individually), and the fact that engagement techniques and playing styles have changed over the years. Therefore, the overall aim of the research programme was to provide the rugby community with objective analysis of the physical demands of scrummaging with a view to establishing effective and safe scrummaging techniques

The focus of the present study was to design, realise and test a new unobtrusive measurement system for assessing the kinematics and kinetics of rugby forwards while scrummaging on the pitch in realistic environmental conditions. At this stage the analysis was focused on the biomechanics of machine scrummaging, leaving to the second phase of the project the analysis of live conditions with two forward packs involved. The reason behind this choice was the need for controllable and repeatable experimental conditions as well as the unavailability of devices that can directly measure forces in live scrums. The underpinning principles employed in the design of the measurement system was to ensure that the measurement system was self-contained and fully portable and data could be obtained on teams unobtrusively,

with players viewing the testing session as much as possible as a simulated training session.

Evaluation criteria: In terms of system performance, it needed to be capable of recording scrummaging forces to a resolution that allowed the identification of differences between playing levels but also differences in force characteristics between selected modified engagement protocols. From previous research [10], the differences in peak forces between different playing levels was approximately 1200 N at each step between under 18 to community to university to international level and the differences between different engagement types was approximately 1000 N. Previous studies which have used field-based video analysis of sport movements have recorded reliability of body orientation and configuration angles of approximately 2° (e.g. [13-15]). It was acknowledged that the analysis of data for this system would be conducted by multiple researchers and so the analysis protocol would need to be able to demonstrate both intra- and inter-operator reliability. Given these conditions the following criteria were set on which to base an evaluation of the fitness of purpose of the developed system:

- measurement of contact forces to within 10% of the expected differences, i.e. < 100 N ;
- reliability of kinematic variables to within accepted limits derived from video-based sport biomechanics research .

MATERIALS AND METHODS

The measurement system integrated three different subsystems for: (I) measuring forces exerted by players; (II) capturing players' movements; and, (III) triggering/synchronizing all the sensors involved in I and II.

I. Force measurement system: A commercially available sled-type scrum machine (Dictator, Rhino Rugby, UK) with approximate mass of 1060 kg was instrumented with a set of force sensors and accelerometers. Strain gauge transducers (8 elements in full bridge configuration for compression; 4 pairs in full bridge configuration for bending) and a piezoelectric accelerometer (3055B2 LIVM, ±50g, Dytran Instruments, USA) were positioned on each of the four pusher arms of the machine so that the three components (lateral, longitudinal and vertical) of the applied force and the acceleration imposed by front row players on each arm of the machine could be measured (Figure 1). The strain gauges and accelerometers were connected to signal acquisition modules (NI 9237 / NI 9234, National Instruments, USA) and were acquired to the computer with 24-bit analogue-to-digital conversion at a sampling rate of 500 Hz. The accelerometers were integrated into the system primarily as a means of benchmarking body-worn sensors for the next phase of testing so will not be further discussed in this paper. During data collection the scrum machine remained stationary due to its weight, its ground spikes and the attachment of additional ratchet straps connected to metal pegs driven into the ground. Any relative movement was negligible and the assumption of rigid body was

reasonably respected. The pusher arms of the machine were oriented horizontally and permitted movement in the axial direction against variable resistance hydraulic dampers set to 'soft' to provide some 'give' during the initial engagement phase (approximately 70 mm) to more closely mimic the visco-elastic behaviour of human-on-human interaction observed in live scrummaging (Figure 1).
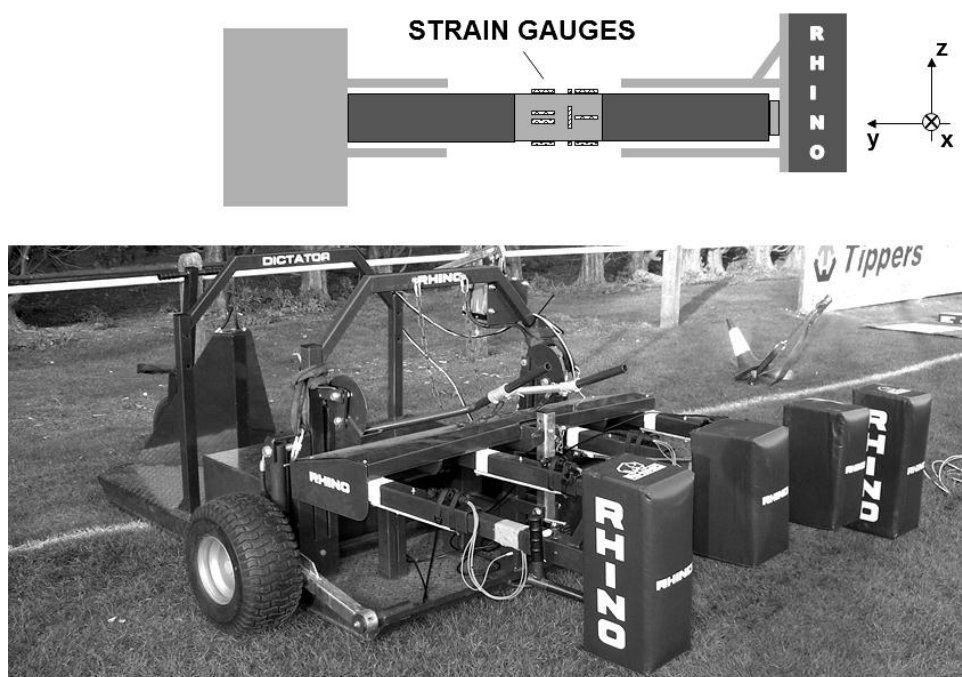
Figure 1. The scrum machine with load sensors attached to four pusher arms and a schematic representation of the strain gauges configuration

Following acquisition, force data were filtered via the implementation of an adaptive zero-lag fourth-order Butterworth filter [16] using custom written software (Matlab 2010, The Mathworks, USA). Minimum and maximum cut-off frequency limits were set to 4Hz and 80 Hz respectively, based on observation of residuals between raw and filtered datasets.

Calibration of the force measurement system: An Instron testing system (Instron 5585H) was used to calibrate the strain transducer arrays in a range between 0 and 10 kN for compression and between 0 and +1 kN for each of the four directions of shear forces (vertical up, vertical down, lateral left, lateral right). Calibration coefficients were obtained for each force component on each pusher arm by linear regressions between the recorded signal (in Volts) and the known load as provided by the Instron device (in Newtons). All regressions were obtained from continuous loading and unloading cycles, one for each direction of load. Mock-up lodging structures were devised for the beam to be tested under the same conditions of use with the scrum machine. Sampling from both the strain gauges and Instron device were set at 20 Hz. Results of the calibration process with coefficients and root mean square differences between known (Instron) forces and measured (strain gauge) forces are provided in Table 1. The relationship between Instron load and strain gauge voltage was found to be linear with R^2 values all greater than 0.987.

Table 1. Calibration results of strain transducers.

Force Component	Parameter	mean	max	min
R_x (lateral)	R^2	0.999	0.999	0.997
	RMSE	9.6	12.7	6.8
R_y (compression)	R^2	0.999	0.999	0.997
	RMSE	58.5	75.4	50.5
R_z (vertical)	R^2	0.995	0.999	0.987
	RMSE	23.4	37.0	4.6

R^2 is the coefficient of determination of the linear regressions; RMSE is the root mean square error (in N) between known load (Instron) and calculated force from calibrated strain data; mean/max/min are the mean, maximum and minimum values taken across the four pusher arms

II. Motion analysis system: The players' movements were synchronously captured by four digital video cameras from three different views (top, left and right). Side cameras (HDR-HC9, Sony, Japan, 50 Hz) were placed on tripods at a distance of 18 m from the centre of the scrum and height of 0.9 m to view the sagittal motion of the "loose-head" and "tight-head" side of the scrum. Top cameras operated at 200 Hz (HVR-Z5, Sony, Japan) and 50 Hz (TRV-900E, Sony, Japan) respectively, and were positioned at a height of 8 m and oriented vertically downwards from the ground by means of two winch-stands and a horizontal truss (Figure 2) to view transverse motion of the scrum. Camera settings were selected dependent on prevailing weather conditions but ensured

manual focus and gave priority to a high shutter speed. A rigid frame 3D calibration object (3.0 x 1.8 x 0.9 m) was used at the beginning of each testing session for multiple 2D calibrations using 4-point projective scaling. Video sequences were later captured and digitised using Vicon Motus software (v.9, Vicon Motion Systems, USA) to allow the reconstruction of the position of selected body landmarks and for the estimation of kinematic variables (displacements, angles and their derivatives). Intra- and inter- rater reliability in the digitising process was assessed by calculating intra-class correlations coefficients (ICC), average bias between repeated measures (avgΔ), and typical error (TE) on a set of kinematic measures taken from a scrummaging trial [17] [18]. The trial was chosen among the ones in which the colour of the players' garments and the light conditions were the most difficult for landmarks identification, so that a worst case scenario could be analysed. Also, we chose the 50 Hz top view camera which covered the largest field of view of all cameras. Three expert operators were asked to digitise 4 points over an interval of 2 seconds (i.e. 101 frames for the top view 50 Hz camera) about the impact of the players against the scrum machine. The selected landmarks were: a static point on the scrum machine; the top of the head, the C7 and the sacrum on the loose-head prop. One of the raters repeated the procedure five times, with an interval of at least two days between each of them. ICCs, avgΔs and TEs were estimated on the following variables that represented paradigmatic measures in the framework of this research: medio-lateral (x) and longitudinal (y) displacements of the 4 landmarks; head, trunk and neck angle of the loose

head prop; medio-lateral (x) and longitudinal (y) velocity of the centre of mass (COM) of the loose-head prop's trunk.
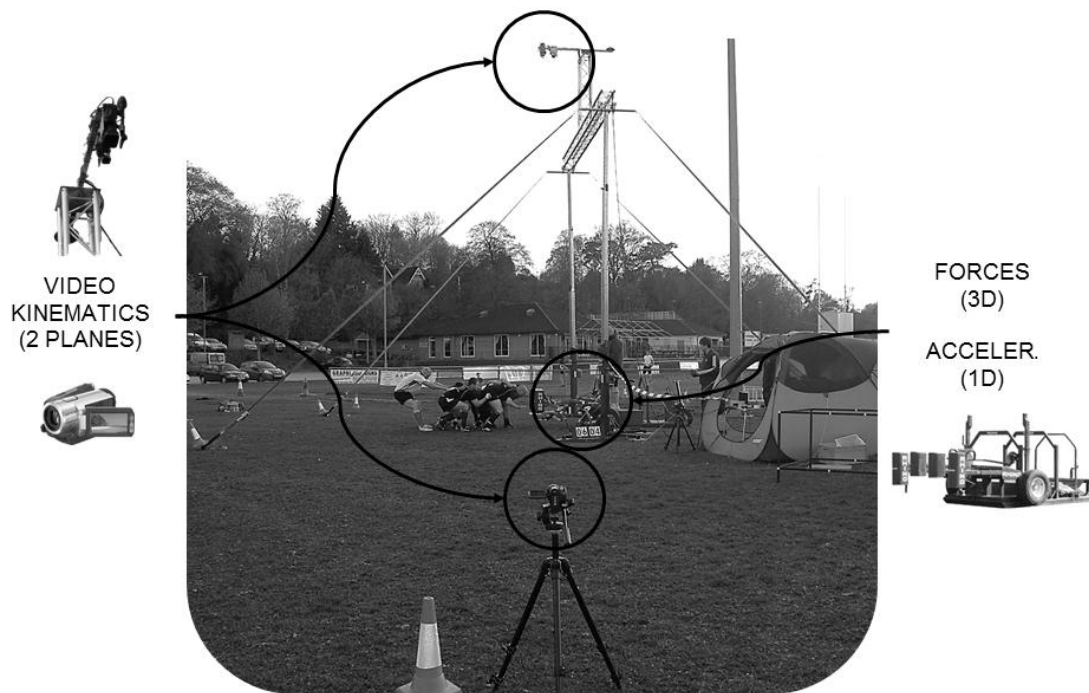

Figure 2. Experimental set-up showing camera positions.

III. Synchronization and audio: The synchronization of the measuring devices was carried out through a reconfigurable embedded control and acquisition system (cRIO-9024, National Instruments, USA) operating in real time, and specially designed software implemented in Labview (v.2010, National Instruments, USA). This system was also used to excite strain gauge circuits and collect force and acceleration signals at a rate of 500 Hz. The control system also simulated the referee's calls during a real scrummage by playing

pre-recorded audio files with standardised timing between the subsequent vocal commands (e.g. "crouch", "touch", "pause", "engage") to ensure consistency for all teams during experimental trials. Triggers were sent to the measurement devices (strain gauges, accelerometers, video cameras) at appropriate times within the audio sequence to ensure collection of the relevant data (Figure 3). Lastly, the control system also triggered LED arrays (banks of 20 LEDs illuminated at 1 ms intervals, Wee Beasty Ltd, UK) visible in each camera view at the instant of the "engage" command" to allow subsequent time synchronisation of video data and force data to within 1 ms.
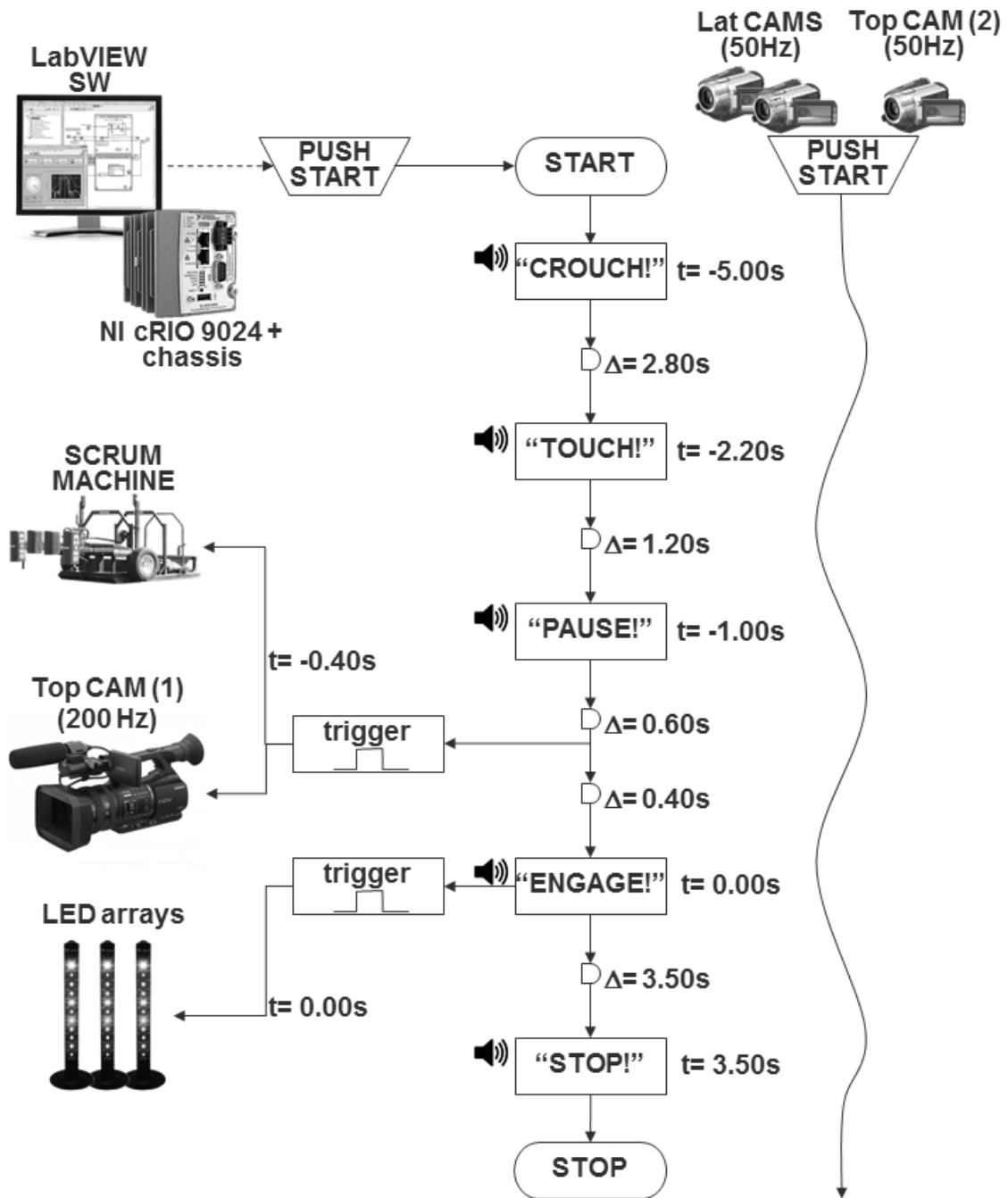
Figure 3. Flow chart depicting control sequence for data acquisition.

This measurement system has been applied to the testing of scrummaging in an initial group of teams from a variety of playing levels, from youth to senior international-level teams and the data have been subjected to initial extraction of key values considered useful to the rugby community, particularly coaches.

RESULTS

The force measurement system acquires force readings in three orthogonal directions from each individual pusher arm which can then be considered in isolation or summed to provide the overall force being applied across the front row interface (Figure 4 and Figure 5). Force acquisition can be repeated for each scrum trial under different engagement conditions to allow comparison (Figure 6) and repeated for each team taking part in the study so that different playing levels can be compared (Figure 7 and Figure 8).
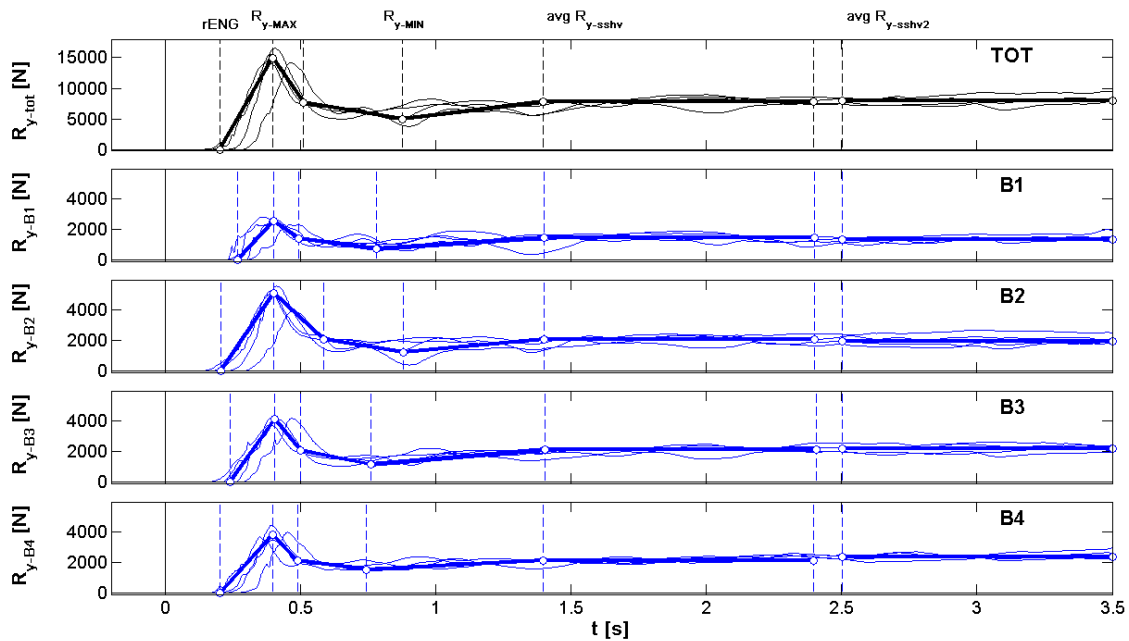
Figure 4. Example of the overall compression force (TOT= sum of the four pusher arms) and the compression forces for individual pusher arms (B1-B4, left to right in the scrum machine) for four trials of one engagement condition for one elite team, with simplified force trace linking median values at key instants (rENG= engage, $R_{y\text{-}MAX}$= peak, drop, $R_{y\text{-}MIN}$= minimum, avg $R_{y\text{-}sshv}$= sustained) of the movement superimposed. Time 0 corresponds to the instant

when the "E" of the "engage" call is played.

Figure 5. Example of the overall force (sum of the four pusher arms) in three directions, compression (R$_y$), lateral (R$_x$) and vertical (R$_z$), for four trials of one engagement condition for one elite team. Time 0 corresponds to the instant when the "E" of the "engage" call is played.
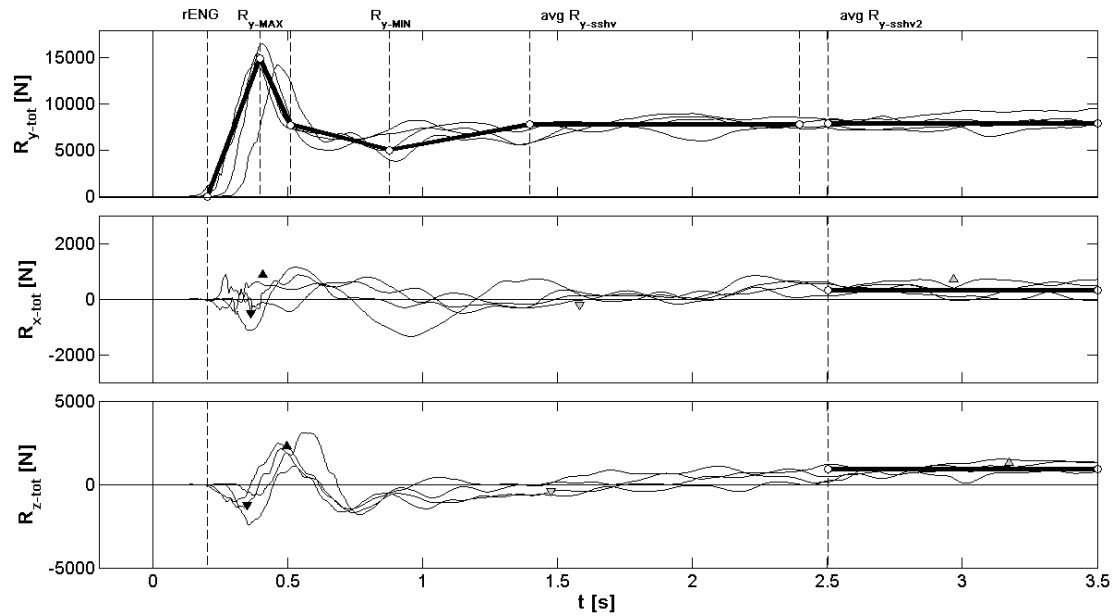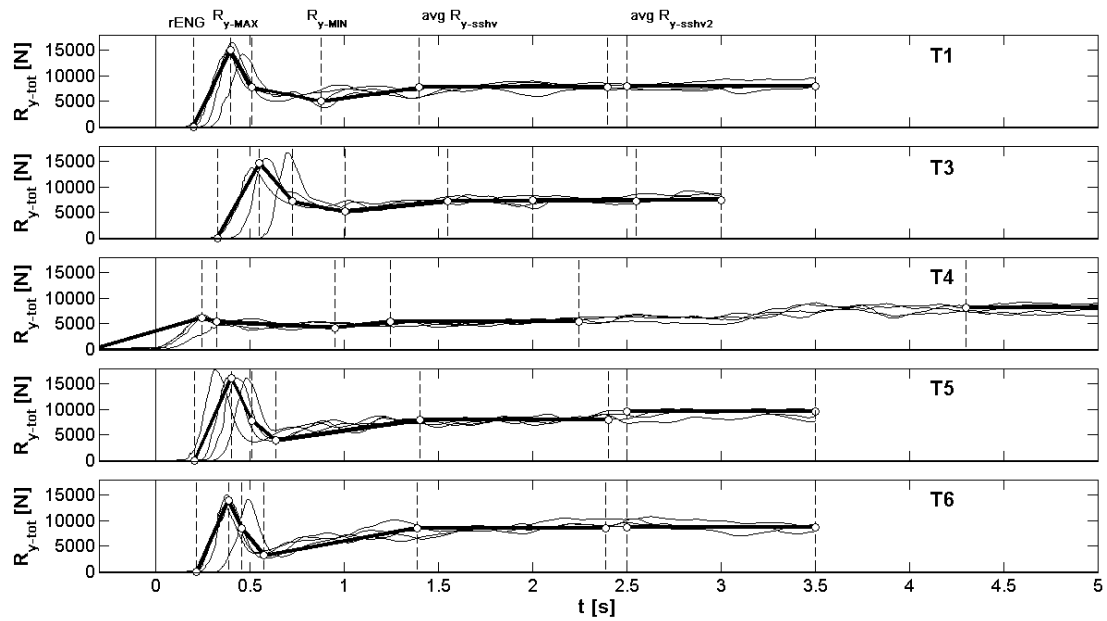
Figure 6. Example of the overall compression force (sum of the four pusher arms) for four trials each of five different engagement techniques (T1-T6, T2 is not used in the comparison because the scrum machine is not fixed in this condition) for one elite team, with simplified force trace linking median values at key instants (rENG= engage, $R_{y\text{-MAX}}$= peak, drop, $R_{y\text{-MIN}}$= minimum, avg $R_{y\text{-sshv}}$= sustained) of the movement superimposed. Time 0 corresponds to the instant when the "E" of the "engage" call is played.

Figure 7. Example of the overall compression force (sum of the four pusher arms, engagement technique T1) for three different playing levels with the force traces having been simplified by linking the median values observed at key instants of the movement (rENG= engage, Ry-MAX= peak, drop, Ry-MIN= minimum, avg Ry-sshv= sustained) of the movement superimposed. Time 0 corresponds to the instant when the "E" of the "engage" call is played.
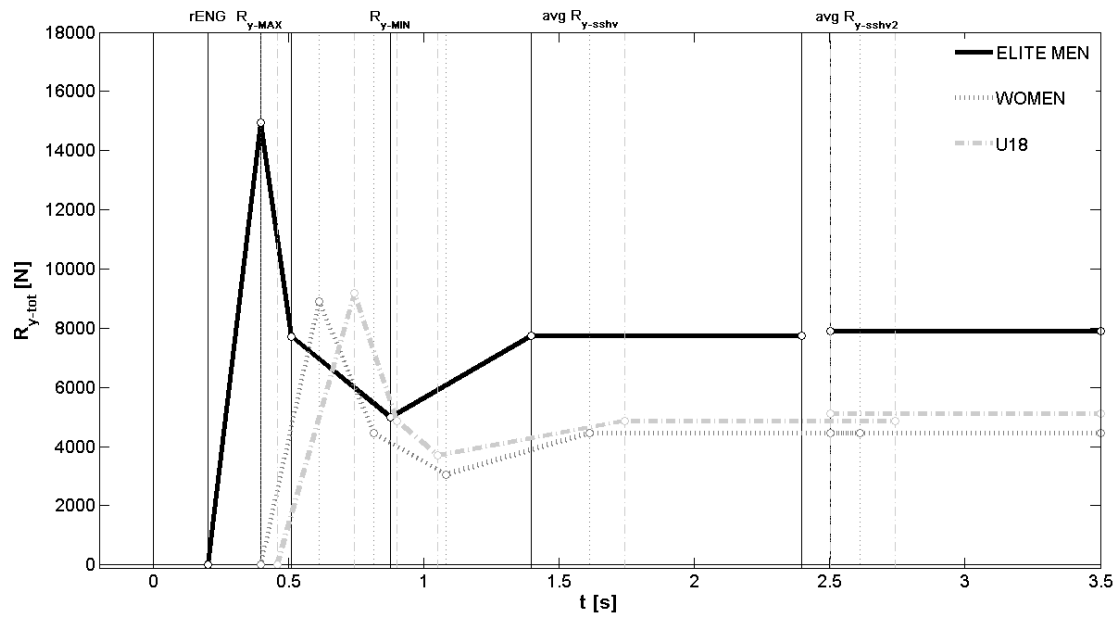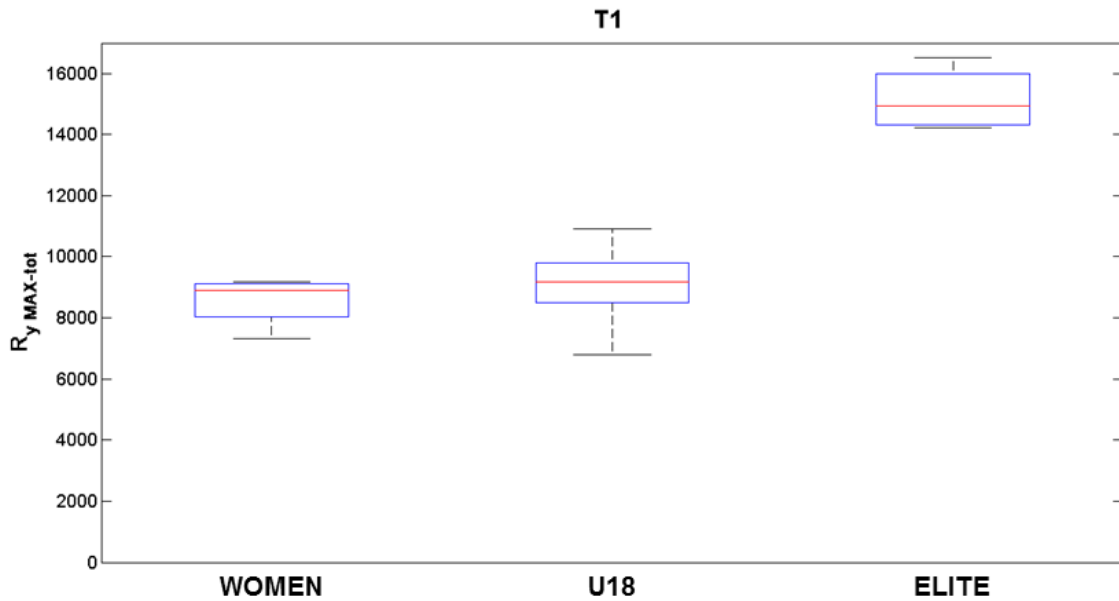
Figure 8. An example of how peak compression force at engagement may change due on playing levels. Boxplots report median and interquartile ranges in the same teams reported in Figure 7. Engagement technique is T1.

Results for digitising reliability showed "substantial" intra-class correlation (> 0.81) for most of the analysed variables for both intra- and inter- rater conditions (Table 2). Values spanned between 1.00 for $C7_y$ and SC_y and values close to 0 for SM_x. However, in the few cases where ICCs were "fair" to "light" both the bias within/between raters and the typical error were small: <0.007 m for displacements; <2.1 deg for segmental/joint angles; and, <0.065 m/s for linear velocities.

Table 2. Intra- and inter- rater reliability of kinematic variables.

			INTRA			INTER		
			ICC	avgΔ	TE	ICC	avgΔ	TE
SM	x	[m]	0.07	0.000	0.003	0.01	0.003	0.005
SM	y	[m]	0.93	0.000	0.002	0.93	0.005	0.002
HD	x	[m]	0.86	0.000	0.004	0.49	-0.003	0.006
HD	y	[m]	1.00	-0.003	0.005	1.00	-0.001	0.007
C7	x	[m]	0.56	-0.002	0.004	0.52	0.004	0.005
C7	y	[m]	1.00	0.000	0.004	1.00	-0.007	0.006
SC	x	[m]	0.97	0.001	0.005	0.97	0.007	0.006
SC	y	[m]	1.00	0.003	0.006	1.00	-0.001	0.009
ϑ_{head}		[deg]	0.84	-0.552	1.292	0.73	1.721	1.568
ϑ_{trunk}		[deg]	0.91	0.329	0.761	0.94	0.787	0.708
ϑ_{neck}		[deg]	0.26	-0.881	1.887	0.23	1.755	2.108
v_{COM}	x	[m/s]	0.82	0.001	0.047	0.89	-0.004	0.045
v_{COM}	y	[m/s]	0.99	0.001	0.057	0.99	0.004	0.065

ICC= intraclass correlation coefficient; avgΔ= average mean difference between repeated measure; TE= typical error. Reported variables are: displacement of the landmark on the scrum machine (SM), on the head (HD), on the 7th cervical vertebra (C7) and on the sacrum (SC) of the loose-head prop; head (ϑ_{head}), trunk (ϑ_{trunk}) and neck (ϑ_{neck}) angles; and, velocity of the centre of mass of the player's trunk (v_{COM}). x and y indicate the direction.

DISCUSSION

The aim of the present study was to design, realise and test a new unobtrusive measurement system for assessing the kinematics and kinetics of rugby forwards while scrummaging on the pitch in realistic environmental conditions. It is concluded at this stage that such a system has been successfully designed and applied in the field, where accurate measurement of forces and collection of player movements have been obtained on a number of rugby teams from a range of playing levels. The implemented measuring system proved to be effective for the analysis of impacts biomechanics in the rugby scrum. The system can be transported to a standard pitch or a suitable area of ground (≥ 36 x 12 m) and assembled in less than two hours by a team of four people. It allows measurement of the 2D kinematics of the players from two different planes of motion (sagittal and transverse) and the 3D kinetics of the interaction between the scrum machine and the front row players. This gives the opportunity of gathering and analysing data about the forces/movements developed by forward packs as they engage in a scrum and how these forces/movements vary across different playing levels and with different engagement techniques

The developed system is not without its resource overhead, taking four trained personnel approximately two hours to set-up to be ready for data acquisition from scrums, this time primarily spent preparing the winch stand and truss frame for the overhead camera views and preparing the instrumentation on the scrum machine. Nevertheless the end result is a data collection set-up which is

entirely self-contained, completely mobile and permits the collection of scrum data from any area of level natural turf.

Initial results extracted from the obtained force time histories demonstrate that the force traces exhibit the characteristic rapid force development and high peak compression forces at engagement of the scrum followed by a drop before more level sustained forces are produced, as observed in previous research [10]. These initial data suggest that engagement forces being produced by contemporary rugby forward packs may be considerably higher than the most cited previously published research [10] but similar to other contemporary data [19] and other existing research [12]. For example, Milburn (1990) recorded peak compression forces during engagement of ~8000 N and sustained pushing forces of ~5800 N from an International forward pack, whereas initial test results on International forward packs from our system return corresponding values of ~16000 N during engagement and ~8000 N for sustained forces. The values for sustained pushing forces are more similar and well aligned with values provided by Quarrie & Wilson [11] of ~7000 N for top-level club players in New Zealand. It seems reasonable at this point to conclude that the differences between studies in force values recorded during the engagement phase will be due to a combination of changes in player actions (techniques rather than increased mass or strength) and differences in measurement technologies used, while the smaller differences observed for sustained pushing forces may reflect slight measurement variations and slight improvements in strength capabilities of contemporary rugby union players. Initial data also seems to reaffirm the need

to investigate the forces produced across different playing levels since force magnitudes and patterns may differ markedly, and also seem to suggest that certain aspects of the mechanics of scrummaging will be influenced by the alternative engagement techniques.

The proposed system proved to be suitable for making kinematic measurements, allowing for a reliable analysis of movement patterns and hence a meaningful comparison of possible changes due to different engagement techniques or playing levels. Both systematic bias and retest errors involved in the digitising procedures appeared in line with existing literature [13-15], with typical errors approximately 6 mm for positions and less than 2 deg for angular measures. These errors were considered small enough if referenced to the magnitude of measures and the expected between-condition changes in the typical variables of interest such as displacements (for which noise was lower than the resolution of the system), segmental/joint angles, and linear velocities.

A full analysis of force and movement patterns at multiple levels of the game will provide a better understanding of the physical demands of scrummaging and how these are influenced by different engagement conditions. This will give the possibility to gain more insight into the type and intensity of demands placed on forwards during scrummaging and, hence, to understand the factors related to the occurrence of acute and chronic injuries. It will also form the quantitative basis for any potential coaching, refereeing modifications or other on field recommendations to manage injury risk whilst maintaining or improving

performance levels. Ultimately, the system is open to future developments that include the integration of further measures (e.g. pressure distribution, wearable sensors) and the study of live, competitive (two teams) scrummaging.

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