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Tacklers' Head Inertial Accelerations Can Be Decreased by Altering the Way They Engage in Contact with Ball Carriers' Torsos

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ABSTRACT

EDWARDS, S., A. J. GARDNER, T. TAHU, G. FULLER, G. STRANGMAN, C. R. LEVI, G. L. IVERSON, and R. TUCKER. Tacklers' Head Inertial Accelerations Can Be Decreased by Altering the Way They Engage in Contact with Ball Carriers' Torsos. *Med. Sci. Sports Exerc.*, Vol. 54, No. 9, pp. 1560–1571, 2022. **Purpose:** This study aimed to investigate how four types of successfully executed, legal front-on, one-on-one torso tackles influence the tacklers' and ball carriers' inertial head kinematics. **Methods:** A total of 455 successful front-on, one-on-one torso tackle trials completed by 15 rugby code players using three-dimensional motion capture were recorded. Tackles differed with respects to the height of the contact point on the ball carrier's torso. A series of mixed general linear models were conducted. **Results:** The tackler sustained the highest peak resultant linear ($P < 0.001$) and angular ($P < 0.01$) head accelerations when contacting the lower torso to execute a "dominant" tackle compared with mid or upper torso, although these latter tackle types had the lowest ball carrier inertial head kinematics. When executing a "smother" tackle technique, a significant decrease in peak resultant linear head acceleration was observed with a vertical "pop" then lock action used, compared with the traditional upper torso tackling technique ($P < 0.001$). **Conclusions:** Modifying the tackler's engagement with a ball carrier's torso, with respect to height and technical execution, alters the inertial head kinematics of the tackler and the ball carrier. The traditional thinking about optimal tackle technique, as instructed, may need to be reevaluated, with the midtorso being a potential alternative target contact height, whereas changes in tackle execution may be relatively protective for tacklers when executing either a dominant or smother tackle. This study provides critical scientific evidence to underpin revised coaching tackling technique interventions that might enhance player safety. Tackles in which the tackler contacts the ball carrier around the midtorso region, rather than lower torso, produce the lowest acceleration and thus may contribute to reducing head injury risk for the tackler. **Key Words:** MOTION CAPTURE, HEAD, CONCUSSION, BIOMECHANICS

The rugby codes are popular international collision sports. There are 6.1 million rugby union players globally, including 3.9 million in Europe, 1.8 million in Rugby North America, and 1.1 million in Oceania (1). Numerous physical collisions (2) occur in game play, in which the defensive players (called the tacklers) attempt to prevent the attacking player (called the ball carrier) from scoring. Most elite-level rugby league players perform an average of 11 to 30 tackles per player per game (3), with some players performing up to 54 tackles per player per game (4). Elite rugby union players typically perform between 4 and 14 successful tackles per game (5).

The tackle event has the greatest risk for concussion (6–11). Approximately 15.4 (95% confidence interval (CI), 9.5–21.3) (12) to 20.4 (11) concussions occurred per 1000 player match

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hours in a professional rugby union, and approximately 14.8 (95% CI, 9.6–23.0) (8) in a professional rugby league (13). Online coaching instruction of safer tackling techniques and for reducing concussion risk is offered by many rugby code governing bodies (e.g., the National Rugby League (NRL) Tackle Safe (14) (www.playrugbyleague.com/), RugbySmart (15) (www.rugbysmart.co.nz/), and BokSmart (16) (www.boksmart.com)). The evidence informing the content of these injury reduction programs to reduce concussion risk is limited (17). The programs are also often based on expert opinion rather than empirical evidence (16), and as a result, the tackling coaching content taught within these programs is informed largely by coaching insight and not scientific evidence. It remains unknown whether or not the content underpinning these tackle interventions results in safer tackling and promotes player safety. For example, the evidence underpinning the NRL Tackle Safe (14) program is based on a small study with elite rugby union players (18) (not rugby league players). The manual identifies a midlevel injury danger area (i.e., "orange zone") when the tackler contacts the ball carrier at the midtorso (between the ball carrier's top of pelvis and base of chest/pectorals), but the safest area or "green zone" is claimed to be when the tackler contacts the ball carrier on the lower torso, the hip area. This color zone system is not supported by recent evidence in professional rugby league (19), where the lowest propensity for head injury assessments was when the tackler contacts the ball carrier's torso (i.e., midtorso), and the highest propensity (excluding rare events with a low incidence, e.g., boot) and the most frequent impact sites are when the tackler contacts the torso either too high (i.e., upper torso or above the sternum/chest) or low (i.e., hip area). This suggests that the NRL Tackle Safe program (14) may incorrectly identify the safest contact area, and that a reassessment of tackle education based on this color zone system is warranted.

Despite 95% of concussions in professional rugby league occurring during the tackle (20), the mechanistic understanding of how tackling technique influences head impact is poorly understood. During a tackle, impulsive forces (incurred through rapid acceleration and deceleration) are applied either directly or indirectly to the head, transferring forces to the brain. These forces can result in a concussion by placing strain on tether points within the brain that may lead to axonal stress, neuroinflammation, and a neurometabolic cascade (21), which may display as postconcussion symptoms. These impulsive forces repetitively sustained but that do not lead a concussion diagnosis (i.e., subconcussive impact) (22), including from tackling (23), are postulated to be linked to neurological issues, although emerging evidence remains inclusive to date (22). Whether the injury mechanism is a single event or culminative incidents, reducing the magnitude of inertial head kinematics of a single tackle or across hundreds of tackles will both achieve an effect to reduce the risk of concussion when tackling regardless of either mechanism.

Accurate in-game three-dimensional (3D) tackling methodologies to measure 3D head kinematics do not currently exist (24). In the laboratory, 3D retroreflective motion analysis is the gold standard for measuring 3D movement. It provides an understanding of 3D head kinematics during the tackle and provides an opportunity to examine the risks of head impact associated with various tackle techniques. However, literature on the 3D retroreflection motion analysis of the tackle technique measured in the laboratory is emerging (24). The ball carrier has previously been found to experience greater changes in head angular velocity and angular acceleration in one-on-one, front-on, tackles in an upper torso compared with a low (25) or mid/low torso (26) tackle height.

The objective of this study was to investigate how four types of successfully executed, legal front-on, one-on-one torso tackles influence the tackler's and ball carrier's inertial head kinematics. It was hypothesized that the tackle techniques (i.e., the dominant, torso & stick (DTS) and the smother ball, pop & lock (SPL), described subsequently) that adhere most closely to tackles with the lowest propensity for head injury assessments (i.e., midtorso) (19,27) would result in significantly decreased peak head linear and angular acceleration for the tackler compared with hip area contact (dominant NRL (DNRL)) or upper torso area (smother NRL (SNRL)).

METHODS

Participants. Amateur or semiprofessional healthy, uninjured, male, adult rugby league or rugby union players ($n = 15$) were recruited from grade competitions. The player characteristics of interest included sport played (i.e., rugby league or rugby union), participant history in the sport(s) (i.e., playing experience in years played), and highest competition level played. At the time of data collection, each participant's age, current competition level, and playing position(s) were recorded. A sample size of 14 participants was deemed sufficient based on using previous published data of the tacklers' trunk flexion angle at contact when performing an upper and lower torso tackle (28). The power calculation was determined for two-tailed t-tests with an error probability and statistical power of 95% using G*Power software (29). Each participant provided written, informed consent before their participation. The University of Newcastle Human Research Ethics Committee (H-2017-0285) approved the study design and methodology.

Experimental procedures. Each data collection session involved two participants, one initially allocated the ball carrier role and the other participant allocated the tackler role. Participants provided informed consent and completed a questionnaire of their sporting participation, and then their anthropometric measurements were recorded for later input into a mathematical model (i.e., body mass, height, and pelvis, xyphoid, and chest depths). Standing in the anatomical position, a static measurement of both participants was recorded. The expert coach guided participants to perform a set of 10 trials of one of four different one-on-one, front-on, torso tackle techniques (Supplemental Digital Content 1, Supplemental Fig. 1, schematic diagram of data collection of the 80 trials performed within a session, http://links.lww.com/MSS/C569) (30). The

NRL coaching manual (31) was followed to guide the instruction of two tackling techniques where the tackler's shoulder contacted the upper torso (SNRL) or hip area (DNRL) of the ball carrier, respectively. The other two tackling techniques were novel variations of the NRL tackles. They involved tacklers being instructed to modify their actions during the contact with the ball carrier: (i) with the tackler lowering the vertical height of his body position and then performing a vertical "pop-up" action that reorients the motion of the ball carrier into an upward direction (SPL), and (ii) by marginally increasing the contact height from the hip area to the midtorso and redirecting the ball carrier into a vertical and backward direction (DTS).

A set of either DNRL or SNRL tackles were always completed first, in a counterbalanced order. Then participants performed a set of the modified tackle technique (DTS or SPL). Each set consisted of five dominant shoulder engagements by the tackler, followed by five trials of nondominant shoulder side engagements. This was implemented in this study because of ambiguous evidence as to whether dominant and nondominant shoulder engagement alters tackle technique (32,33).

The expert coach instructed the participants on how to perform the specific technique correctly before engaging in the 10 trials of that technique. Several familiarization trials of that technique were performed with coaching feedback delivered. The coach evaluated every tackle repetition and deemed it successful if, in his assessment, the correct technique had been executed. Reasons for rejection of a tackle attempt included the following: if the tackler's head was not on the side of the ball carrier's body (right shoulder side tackle, left side of ball carrier's body) or if the ball carrier was holding the ball on the incorrect side (Fig. 1).

After the participants completed the 40 tackle trials (4 types, 10 trials per type), the roles of the participants were reversed (i.e., the tackler became the ball carrier and *vice versa*), and another static trial in the anatomical position was performed, followed by another 40 (4 types, 10 of each) tackling trials. The total experimental protocol lasted approximately 3 h.

Expert coach. The expert coach for this study was a recently retired dual international rugby league and rugby union representative player, with junior and senior rugby league and rugby union coaching experience. This expert coach developed the nontraditional front-on tackle technique (SPL, DTS) used in this study. All sessions were attended by the expert coach who gave coaching instruction to all participants before undertaking the data collection session. The coach also provided guidance and feedback to all participants throughout each session.

Tackling trials. Every trial started with the ball carrier and tackler in a stationary position, ~4 m apart. To standardize the approach speed, thereby limiting the confounding factor of player speed (10,34), the participants were instructed to simultaneously run toward each other engaging in contact at 80% game intensity, whereas each player speed was measured using the 3D motion caption system. This instruction led to a slow tackle speed (as per the definition of walking or jogging into the tackle).

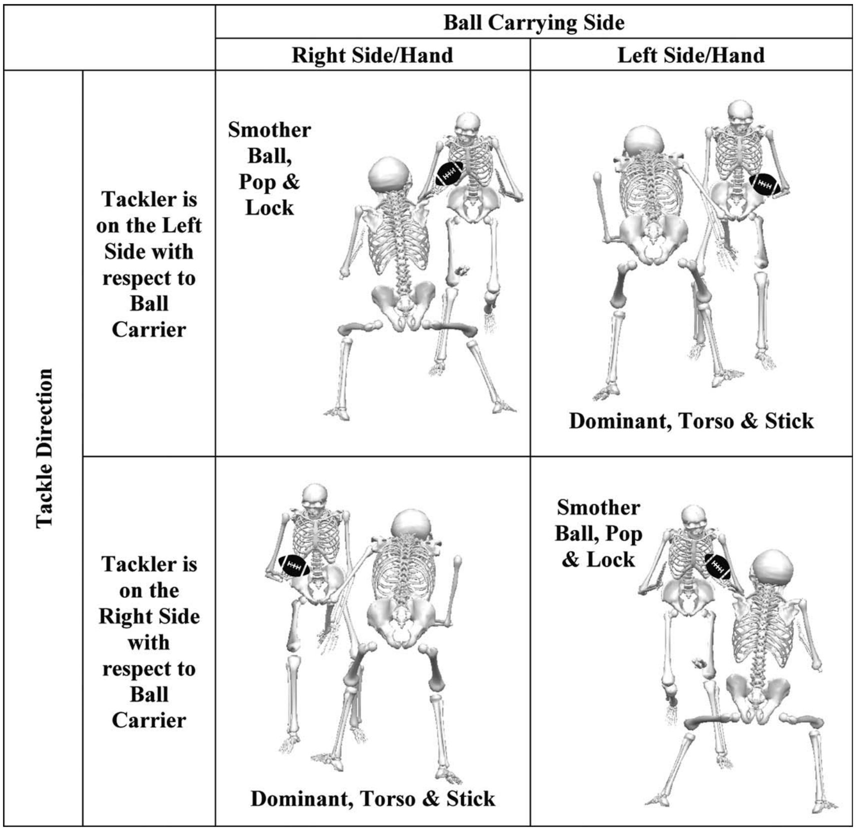

FIGURE 1—Matrix of tackling type selection in a game.

The tackle was not completed to the ground in this study: (i) because player contact, rather than ground contact, causes most tackle injuries (35), and (ii) because of the injury risk for the participants that is associated with the skin-mounted retroreflective markers impacting with the ground. As a result, tackles in this study were done at slower speed with less force (i.e., 80% game intensity) than would typically occur in field situations in training and matches. The tackle surface was a 20-m^2 matted surface (1000 × 1000 × 40-mm jigsaw mat underlay, 2000 × 1000 × 40-mm Tatami Judo mat (Southern Cross Mats, Sydney, New Southwales, and Melbourne, Victoria)). Rest periods were 30 s between trials and a ~5-min rest between each new technique set of 10 trials.

The NRL Coaching Manual (31) and Tackle Safe program (14) outline the technique instruction for the traditional, one-on-one, front-on, torso tackle. Detailed within these manuals is an instruction on how tacklers should be as upright as possible when approaching the tackle, then bend their knees while keeping their shoulders higher than hip level to drop their body position as they are about to execute the tackle. It outlines that tacklers should use their shoulder to make the contact, position their head to the ball carrier's side, and maintain alignment of their neck with the spine by keeping their head up and straight. To take the ball carrier to the ground, the instructional manual outlines that the tackler should use a strong leg drive and use the ball carrier's momentum. Tackle height in accordance with previous research (18) is recommended in the Tackle Safe program (14) and defines "torso contact" as "green zone" (hip area), "orange zone" (midtorso, between the top of the pelvis and the base of the chest/pectorals), and "red zone" (upper torso, base of the chest/pectorals to the line of the shoulders). In this study, the tackle heights associated with each tackle type were the hip area (DNRL), midtorso (DTS), mid/upper torso (SPL), and upper torso (SNRL), respectively (Table 1).

Table 1 details the categorization of each of the tackle types, and how, when, and why a tackler would use each tackle type within a game are explained in detail. The purpose of the two smother tackle types (SPL, SNRL) is to wrap up ball carriers to prevent offloading of the ball, to prevent the ball carriers from using their forearm/ball as a defensive strategy to bump off the tackler, and to control the ball carrier when taking the tackle to the ground to slow the play-the-ball. The two variants of the smother tackle in this study differ from one another in the way the tackler engages in contact to wrap up the ball and ball carrier, and should be used by tacklers when they are on the ball-carrying side of the ball carrier. In contrast, the strategy when performing the two dominant tackle instructions (DTS, DNRL) is to bring the ball carrier to the ground to enable the tackler and defensive team a longer duration to get back onside for the next play of the ball. The key differences between these dominant strategies are contact height and the angle of the force application by the tackler (Table 1). Figure 1 outlines a tackle matrix that describes when tacklers should execute a dominant tackle (i.e., when the tackler is on the non–ball-carrying side of the ball carrier) or a smother tackle (i.e., when the tackler is on the ball-carrying side of the ball carrier) in a game situation.

Data collection. A full-body retroreflective marker set (39) was placed on both the tackler and the ball carrier participants on each of their heads, forearms, upper arms, hands, trunk, pelvis, thighs, shanks, and feet. A 15 Oqus 700+ camera optoelectronic motion capture system (300 Hz; data collection volume, 10 m × 10 m × 6 m) using Qualisys Track Manager software (version 2018.1; Qualisys AB, Göteborg, Sweden) recorded the full-body 3D kinematic of both participants for each tackle trial. To adhere to the Nyquist sampling theorem, the sampling rate in this study was determined by spectral analysis (40) of 3D head linear and angular acceleration indicating that the median frequency in which 99% of the data occur below was 49 Hz.

Visual 3D software (version 6; C-Motion, Germantown, MD) was used to undertake the 3D data analysis. The raw kinematic data were interpolated with a cubic spline and then filtered by an 18-Hz cutoff frequency, zero-phase fourth-order low-pass Butterworth digital filter before calculating kinematic variables. An 18-Hz cutoff frequency was determined by performing a residual analysis (40) of the raw 3D position of head markers, with a median frequency of 12 Hz (range, 9–14 Hz) reported from the analysis. The segmental masses and inertial properties were modeled as per the protocol of Schaefer et al. (39). To calculate joint and segment angles, a local Cartesian coordinate system was used (x axis mediolateral; y axis anterior–posterior; and z axis superior inferior directions).

Three stages of the tackle were identified, in the following order of appearance: (i) two steps before contact (step 2); (ii) one step before contact (step 1); and (iii) at contact, between the tackler and the ball carrier. These stages were defined according to the procedures outlined by Edwards and colleagues (30). The tackler's joint angles (ankle, knee, hip, lumbopelvic (lumbar segment relative to the pelvis segment), thoracolumbar (lumbar segment relative to the thoracic segment), trunk–pelvis (trunk segment relative to the pelvis segment)) and segment angles (thigh segment, pelvis segment, and trunk segment relative to the laboratory coordinate system) at each of these three sequences were reported. The resultant center of mass velocity at the time of precontact (defined as the maximum value before contact) and at contact was used to define the approach speed and speed at contact of each player.

Statistical analysis. Of the 600 trials collected across all 15 participants, there was a total of 455 (75.8%) successful trials included in the statistical analysis. Unsuccessful trials were identified by the expert coach during the data collection as attempts where the tackler did not adhere to the tackling instruction guidelines outlined in Table 1. Final categorization of the trials as successful or nonsuccessful (n = 145) was reviewed together by two authors (the expert coach and the biomechanics expert) who made their decision based on viewing the Visual 3D software animation of each trial. These unsuccessful trials were then excluded from the final analysis. The successful trials were used to calculate the means and SD for all variables across the four tackling instructions when engaging in the dominant and nondominant shoulder side for joint angles, segment angles, approach speed, and speed at contact.

TABLE 1. Categorization of the tackling instruction.

Tackle Information	Smother Tackle		Dominant Tackle	
Tackle Type	**SNRL**	**SPL**	**DTS**	**DNRL**
Tackle objectives	Prevent the ball carrier offloading the ball and/or wrap up the ball and ball carrier together to (i) prevent the ball carrier using his forearm/ball as a defensive strategy to bump off the tackler and (ii) control the ball carrier when taking the tackle to the ground to slow the play-the-ball.		By placing ball carriers on their back, it enables the defensive team a longer duration to get back onside for next play. This tackle also aims to move the ball carrier laterally instead of driving the ball carrier backward to allow defensive teammates to assist in the tackle.	By placing ball carriers on their back, it enables the defensive team longer duration to get back onside for the next play. This tackle also aims for the tackler to dip under the ball-carrying side of the attacker and drive the attacker backward to be dominant in the tackle.
Contact area on the ball carrier as defined by Tierney and Simms (18)	Upper torso (base of chest/pectorals to line of the shoulders)	Mid/upper torso (base of the chest)	Midtorso (top of the pelvis and base of the chest/pectorals)	Hip area (base of the pelvis to the top of the pelvis)
Tackler makes contact with	Shoulder	Chest/pectoral region	Shoulder	Shoulder
Tackler torso position (in the sagittal plane) as defined by Stokes et al. (36)	Upright/partially bent at waist*	Partially bent at the waist	Partially bent at the waist	Fully bent at the waist
Tackle engagement description	Tacklers use their chest and wrap both arms around the ball carrier as defined by Fuller et al. (37).	Tacklers use their pectoral on the ball carrier's forearm and ball to wrap up both the arms around the ball carrier (i.e., tackler right pectoral, ball carrier's right forearm/ball).	Tacklers use their shoulder to engage in contact with the ball carrier's abdomen (i.e., midtorso; tackler right shoulder, ball carrier's non–ball-carrying side).	Tacklers use their shoulder to engage in contact with the ball carrier's lower torso.
Tackle execution description	Tacklers position themselves underneath the ball and then execute the tackle.	Tacklers lower the vertical height of their body position and then perform a vertical pop-up action to reorient the motion of the ball carrier into an upward direction.	Tackler moves the ball carrier in a backward and upward direction during the tackle and places the ball carrier on his back at the completion of the tackle.	Tackler moves the ball carrier in backward direction during the tackle and places the ball carrier on his back at the completion of the tackle as defined by King et al. (13).
Tackler head position	Tacklers position their heads within the ball carrier's shoulder when engaging in contact and may not avoid the ball carrier using his forearm/ball to bump the tackler away.	Tacklers position their heads outside the ball carrier's shoulder when engaging in contact.	As the tackle is executed on the non–ball-carrying side, the tackler's head is away from the ball carrier's forearm, which avoids the ball carrier using his forearm/ball to bump the tackler away.	Tacklers duck their heads before contact and may end up beside or in front of the ball carrier depending on the movement of the ball carrier before the contact.
Gaze direction as per Hendricks et al. (38)	Up and forward, gaze focused on ball carrier	Up and forward, gaze focused on ball carrier	Up and forward, gaze focused on ball carrier	Down, gaze pointing toward the ground (not the ball carrier)
When to use tackle (ball-carrying side)	Not specified	Ball carrier is holding ball on same side as tackler (i.e., ball in the right hand of ball carrier, tackler is to the left side with respect to the ball carrier, and performs the tackle with his right side).	Ball carrier is holding ball on the opposite side as tackler (i.e., ball in the left hand of ball carrier, tackler is to the left side with respect to the ball carrier and performs the tackle with his right side).	Not specified
Traffic light system defined by the Tackle Safe program (14)	Red zone	Amber/red zone	Amber zone	Green zone
Revised traffic light system as per this study's finding	Orange zone—tackler Orange zone—ball carrier	Green zone—tackler Red zone—ball carrier	Green—tackler Orange zone—ball carrier	Red zone—tackler Green zone—ball carrier

*Dependent on the vertical height of the ball carrier and tackler, and where the ball carrier is holding the ball.

A series of mixed general linear models were performed using IBM SPSS (version 26.0, IBM SPSS Statistics for Windows; IBM Corp., Armonk, NY) to determine if any significant changes ($P < 0.05$) occurred within the means of any outcome variable(s) between the four tackling instruction (DNRL, DTS, SNRL and SPL). There was one repeated-measure factor (step 2, step 1, contact) and four subject factors of participant (n = 15), instruction or tackle type (n = 4), dominant shoulder side (n = 2), and count (n = 5). The "instruction" factor represented the four different tackling technique instructions. The "dominant shoulder side" factor defined whether the tacklers contacted the ball carrier's torso with their dominant or nondominant shoulder side. The "count" factor defined one of the five trials performed per condition (e.g., five trials performed for DNRL using the dominant shoulder side). Participant and count were included as factors to account for the different number of successful trials per person within each tackle type. To determine if any significant changes ($P < 0.05$) occurred within peak approach speed or speed of contact between the four tackle types, there were five subject factors, namely, participant (n = 15), instruction (n = 4), dominant shoulder side (n = 2), count (n = 5), and player role (n = 2). The "player role" factor defined whether the speed was of the tackler or the ball carrier.

Each analysis was performed with three different repeated covariance types (compound, heterogenous compound symmetry, and unstructured). As outlined by Burnham and Anderson (41), the scaling criterion values were calculated using the Akaike information criterion from each covariance type model, and the model that was selected resulted in the minimization of the scaling criterion value. If the scaling criterion value was <10 between the two models, the model with the less complex structure was chosen.

The Akaike information criterion negated the requirement to satisfy the normality of distribution and sphericity assumptions for each variable. Main effects of instruction, dominant shoulder side, and the repeated measure variable (three stages of the tackle) and their respective two-way and three-way interactions were performed, and pairwise contrast types were adjusted for multiple comparison using the least significant difference. The tackler's rear lower limb was defined as the foot that made foot-ground contact at step 2, and the lead lower limb was defined as the other foot that made foot-ground contact at step 1.

The successful trials analyzed for the peak resultant head acceleration variables ranged from 428 to 439 of the pool of 455 successful cases. For each angle variable across each of the three time points (step 2, step 1, contact), there were a possible 1365 cases that were inputted in the mixed model general linear analysis. This led to cases included in the analyses ranging from 1228 to 1360 for joint angles and 1296 to 1359 for segment angles. Missing kinematic data occurred in some trials because there were fewer than three retroreflective markers tracking the relevant segment(s) because of marker(s) becoming occluded or unadhered to the body from body contact in the tackle and/or the tackler's sweat.

RESULTS

Participant characteristics. The participants played both rugby codes (n = 5), only rugby league (n = 2), or only rugby union (n = 8). The highest level of competition played was national (n = 1), followed by state (n = 2), regional (n = 3), and club rugby (n = 9). Playing experience was 12.7 ± 6.3 yr (range, 4–30 yr) with both forwards (n = 8) and backs (n = 7) included in the sample.

Peak resultant head accelerations. The DNRL (i.e., hip area) tackle type resulted in significantly higher peak resultant linear and angular head accelerations for the tackler than the other three tackle types (Table 2). For the ball carrier, DNRL produced the smallest peak linear and angular head accelerations. The SPL (i.e., mid/upper torso tackle type) produced lower peak resultant angular head accelerations for tacklers but higher head accelerations for ball carriers, compared with both SNRL and DTS. The ball carriers' peak resultant linear head acceleration was higher during SPL compared with the SNRL and DTS.

Kinematics at the time of step 2, step 1, and contact. Table 3 shows the means and SD of the sagittal plane angles of various joint and segment angles for the tackler during these four tackle instructions. For each tackle instruction, the tackle is divided into three phases (step 2, step 1, and contact), and the dominant and nondominant sides are compared for each tackle type. Supplemental Figure 2 (Supplemental Digital Content 2, http://links.lww.com/MSS/C570) provides a graphical representation of the mean of all the successful trial across 15 participants for the joint and segment angles from pretackle (0%) to posttackle (100%) across the four tackle instructions,

TABLE 2. Peak resultant head accelerations (mean ± SD, median (95% CI), and mixed general linear model of the main effects and interactions) of the tackler across the four tackling instructions.

	SPL		SNRL		DTS		DNRL	
Peak Head Acceleration	**DOM**	**ND**	**DOM**	**ND**	**DOM**	**ND**	**DOM**	**ND**
Tackler angular (rad·s^{-2})	331 ± 134^{a}	379 ± 205^{a}	337 ± 189^{a}	365 ± 215^{a}	321 ± 136^{a}	321 ± 110^{a}	420 ± 180	410 ± 167
	262 (276–392)	262 (276–392)	341 (319–438)	327 (305–434)	283 (284–390)	305 (282–386)	406 (364–475)	437 (351–466)
Tackler linear (g)	3.9 ± 1.4^{a,b}	4.4 ± 2.0^{a,b}	4.4 ± 1.9^{a,c}	5.1 ± 2.6^{a,c}	4.5 ± 1.6^{a}	4.7 ± 1.7^{a}	6.2 ± 2.3	5.9 ± 2.1
	3.6 (3.4–4.8)	4.0 (3.5–5.0)	4.0 (3.9–5.5)	4.5 (4.5–6.0)	4.5 (4.1–5.5)	4.2 (4.2–5.6)	6.0 (5.5–6.9)	6.0 (5.1–6.6)
Ball carrier angular (rad·s^{-2})	300 ± 163^{a,b}	299 ± 118^{ba}	214 ± 99^{a,c}	214 ± 96^{a,c}	259 ± 105^{a,b}	303 ± 155^{ba}	168 ± 76	164 ± 89
	273 (252–343)	270 (251–344)	217 (179–269)	204 (173–263)	254 (216–309)	307 (250–342)	156 (126–214)	138 (122–209)
Ball carrier linear (g)	5.0 ± 2.0^{a,b}	5.2 ± 1.7^{a,b}	3.7 ± 1.6^{a,c}	3.9 ± 1.3^{a,c}	4.1 ± 1.5^{a,b}	4.8 ± 1.9^{a,b}	3.0 ± 1.1	2.9 ± 1.1
	4.7 (4.4–5.6)	5.2 (4.6–5.9)	3.7 (3.3–4.4)	4.0 (3.4–4.5)	4.0 (3.5–4.7)	4.7 (4.1–5.3)	2.9 (2.5–3.5)	2.7 (2.4–3.4)

					95% CI	
Effect	***F***	***P***	***Post Hoc***	***P***	**Lower**	**Upper**
Tackler head angular acceleration						
Instruction	$F_{3,420}$ = 7.2	0.000	DNRL higher peak head angular acceleration than DTS	0.000	112	45
			DNRL higher peak head angular acceleration than SPL	0.003	20	96
			DNRL higher peak head angular acceleration than SNRL	0.013	11	97
Tackler head linear acceleration						
Instruction	$F_{3,420}$ = 25.9	0.000	DNRL higher peak head linear acceleration than DST	0.000	1.6	0.8
			DTS higher peak head linear acceleration than SPL	0.001	0.3	1.0
			DNRL higher peak head linear acceleration than SPL	0.000	1.4	2.3
			DNRL higher peak head linear acceleration than SNRL	0.000	0.6	1.5
			SNRL higher peak head linear acceleration than SPL	0.001	1.2	0.3
Ball carrier head angular acceleration						
Instruction	$F_{3,431}$ = 52.5	0.000	DNRL lower peak head angular acceleration than DTS	0.000	89	135
			SNRL lower peak head linear acceleration than DTS	0.000	34	83
			DNRL lower peak head angular acceleration than SPL	0.000	152	107
			DNRL lower peak head angular acceleration than SNRL	0.000	75	31
			SNRL lower peak head linear acceleration than SPL	0.000	52	100
Ball carrier head linear acceleration						
Instruction	$F_{3,430}$ = 65.6	0.000	DNRL lower peak head angular acceleration than DTS	0.000	1.1	1.8
			DTS lower peak head angular acceleration than SPL	0.001	1.2	0.3
			SNRL lower peak head linear acceleration than DTS	0.009	0.1	0.8
			DNRL lower peak head angular acceleration than SPL	0.000	2.5	1.8
			DNRL lower peak head angular acceleration than SNRL	0.000	1.3	0.7
			SNRL lower peak head linear acceleration than SPL	0.000	0.8	1.6

DOM, dominant-side shoulder engagement; ND, nondominant-side shoulder engagement.
[a]Statistically significantly different from DNRL.
[b]Statistically significantly different from SNRL.
[c]Statistically significantly different from DTS.

and a supplemental video provides an animation video of these tackle instructions by a single participant (Supplemental Digital Content 3, Supplemental Video, successful tackles exemplars, http://links.lww.com/MSS/C571). The mixed general linear model of the main effects and interactions of these angles are shown in Supplemental Tables 1–7 (upper joint angles in Supplemental Tables 1–4 and lower joint angles in Supplemental Tables 5–7; Supplemental Digital Content 1, results of the mixed general linear model of the main effects and interactions for the tacklers, http://links.lww.com/MSS/C569). The means and SD of frontal and transverse joint angles (Supplemental Tables 8 and 9, Supplemental Digital Content 1, the tackler's frontal and transverse angles, http://links.lww.com/MSS/C569) and segment angles (Supplemental Tables 10 and 11, Supplemental Digital Content 1, the tackler's lower limb segment angles (Table S10) and the tackler's torso segment angles (Table S11), http://links.lww.com/MSS/C569), and the results of the mixed general linear model (Supplemental Tables 12–16, Supplemental Digital Content 1, results of the mixed general linear model, http://links.lww.com/MSS/C569) are also in the supplemental section.

There were numerous differences in sagittal plane kinematics between the different types of tackle instruction. Some of key findings are summarized hereinafter.

The SPL technique displayed the least head flexion at all stages of the tackle (overall, step 2, step 1, contact), trunk–pelvis flexion (overall, step 2, step 1, contact), thoracolumbar flexion (overall, step 2, step 1, contact), lumbopelvic flexion (overall, step 2, step 1, contact), lumbopelvic left lateral flexion (contact, step 2, step 1, contact), lead hip flexion (contact, step 2, step 1, contact), and rear hip flexion (overall, step 1, contact) when compared with the DNRL and DTS techniques.

The DNRL technique displayed the greatest head flexion (overall, step 2, step 1, contact) and trunk–pelvis flexion (overall, step 1, contact) of all techniques. When compared with the DTS, the DNRL also displayed greater thoracolumbar flexion (overall, step 2, step 1, contact) and lead hip flexion (overall, contact, step 1).

Player speed. The ball carriers ran with a consistently higher approach speed and speed at contact than the tacklers (Supplemental Table 17, Supplemental Digital Content 1, resultant center of mass velocity of the tackler, http://links.lww.com/MSS/C569). Peak approach speed for the tackler revealed a significant main effect of tackle type and player role. The tackler's approach speed was faster in the DNRL tackle compared with all other tackle types, and the SNRL was faster than SPL and DTS. The ball carrier's approach speed was slower in a DNRL than DTS and SPL, and the SNRL was slower than DTS. However, at contact, ball carriers' speed was significantly faster when being engaged in the tackle with their nondominant shoulder side than their nondominant shoulder side.

DISCUSSION

This 3D biomechanical study examined a large data set of successful front-on, one-on-one, torso tackles. This study finds that both tackle height and the technique used by the tackler to engage in contact with the ball carrier's torso can alter head impact kinematics for both the tackler and the ball carrier.

The key outcome of this study is that the lowest torso contact height (i.e., contact at the hips), which is traditionally thought to be safest and is instructed as the green zone in coaching manuals (14) (DNRL), produces the highest linear and angular head acceleration for the tackler and the lowest linear and angular head acceleration for the ball carrier. Tackles that contact at the midtorso (above the hip area but below the pectorals; DTS) or the area delineating the mid and upper torso (SPL) produce lower peak head accelerations in tacklers but higher accelerations in ball carriers. Given that head injury has been more likely found in tacklers (19) and may be the result of excessive head acceleration, this finding suggests that traditional thinking about optimal tackle technique, as instructed, may need to be reevaluated, at least from the perspective of the tackler, with the midtorso being the recommended target contact height. Specific findings and their implications are described hereinafter.

Inverse relationship between peak head acceleration between the ball carrier and tackler. Consistent with the literature (25), this study found that the ball carrier's peak linear and angular head acceleration increases as the contact height in the tackle increases, such that the highest peak linear and angular head acceleration during front-on tackles occurs for upper torso contact. Importantly, however, the opposite was found for tacklers, because the highest peak linear and angular head acceleration was observed for hip area contact (DNRL) and decreased when contact was the mid (DTS) and mid/upper torso, particularly when the tackler was instructed in the SPL method (Table 3). Considering that most head impact injuries are sustained by a tacklers rather than ball carriers (10,19,34), tackling technique recommendations that reduce head impact acceleration forces for tacklers may need to be considered as per the current study methods. This recommendation must, however, be evaluated as a trade-off between tackler and ball carrier heads, because they display reciprocal peak head accelerations depending on the tackle height. Our suggestion is that the modified tackle techniques described here (Table 1, see the revised traffic light system) might produce the best overall risk outcome, with the lowest head accelerations for tacklers and moderate accelerations in ball carriers.

Challenging the injury safety assumptions of the NRL tackle safe tackle color zones based on contact height. The Tackle Safe program (14) recommends a green zone (lower torso) tackle height, which, from the perspective of the ball carrier, agrees with our findings and is in accordance with previous research on the influence of tackle height on ball carrier head kinematics (18). It also identifies an orange zone (midtorso) and finally the red zone (upper torso) (14). Our findings challenge the safety assumptions of these color zones for the tackler. We find that the green zone (i.e., DNRL) had the highest tackler peak linear and angular head acceleration when tackling front-on, followed next by the orange zone

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TABLE 3. The tackler's angles (mean ± SD) at three key tackle phases for lead and rear lower limb across the four tackling instructions.

Angle	Event	Lower Limb	SPL		SNRL		DTS		DNRL	
			DOM	ND	DOM	ND	DOM	ND	DOM	ND
Ankle dorsiflexion (+)/plantarflexion (–)	Step 2	Lead	8.1 ± 11.7	6.2 ± 9.0	–1.2 ± 10.8	5.3 ± 10.9	1.7 ± 8.3	2.5 ± 10.1	6.1 ± 9.1	1.7 ± 9.9
	Step 1	Lead	1.7 ± 11.9	3.2 ± 9.0	–2.2 ± 10.8	–4.4 ± 11.4	0.8 ± 8.4	2.1 ± 9.7	–4.3 ± 12.0	–3.5 ± 11.5
	Contact	Lead	19.9 ± 11.0	23.8 ± 9.5	11.2 ± 9.7	9.7 ± 9.5	9.9 ± 11.4	17.0 ± 11.5	10.7 ± 9.4	13.6 ± 12.1
	Step 2	Rear	3.8 ± 9.2	5.7 ± 8.7	2.8 ± 9.2	–0.1 ± 8.4	3.9 ± 7.4	5.9 ± 9.5	2.8 ± 8.7	2.9 ± 10.7
	Step 1	Rear	20.6 ± 17.8	18.1 ± 15.6	10.1 ± 16.6	18.9 ± 13.0	14.1 ± 12.9	12.5 ± 14.8	17.0 ± 12.3	14.2 ± 12.0
	Contact	Rear	22.7 ± 14.4	22.3 ± 11.3	16.1 ± 11.1	17.7 ± 9.4	19.0 ± 9.5	20.4 ± 12.1	16.8 ± 14.1	18.1 ± 12.9
Knee flexion (+)/extension (–)	Step 2	Lead	57.2 ± 13.9	56.1 ± 17.0	49.6 ± 12.9	57.3 ± 17.3	49.3 ± 14.0	56.4 ± 16.1	53.1 ± 16.6	51.9 ± 16.1
	Step 1	Lead	53.6 ± 16.1	57.3 ± 15.0	52.8 ± 14.4	49.0 ± 14.1	50.5 ± 13.5	55.0 ± 11.9	45.5 ± 13.7	55.4 ± 15.5
	Contact	Lead	75.5 ± 10.3	80.0 ± 9.4	72.3 ± 12.3	73.8 ± 11.9	69.9 ± 17.6	80.3 ± 11.7	73.9 ± 15.3	78.6 ± 13.2
	Step 2	Rear	76.4 ± 17.2	77.4 ± 15.2	74.5 ± 18.2	72.0 ± 21.0	75.1 ± 17.4	78.8 ± 19.2	70.2 ± 23.0	78.0 ± 21.1
	Step 1	Rear	73.7 ± 15.1	71.2 ± 15.9	72.8 ± 15.4	75.5 ± 12.2	70.4 ± 14.9	73.0 ± 14.7	76.0 ± 10.5	74.2 ± 14.0
	Contact	Rear	78.6 ± 15.6	74.5 ± 17.3	81.2 ± 11.1	81.7 ± 14.9	77.0 ± 13.1	79.2 ± 16.4	78.9 ± 18.0	78.2 ± 15.4
Hip flexion (+)/extension (–)	Step 2	Lead	53.8 ± 18.1	52.8 ± 20.9	58.8 ± 19.2	55.5 ± 22.6	51.8 ± 19.7	58.5 ± 20.5	57.4 ± 16.2	59.0 ± 19.2
	Step 1	Lead	67.1 ± 16.4	62.3 ± 16.3	71.2 ± 17.3	69.4 ± 19.6	65.1 ± 16.9	68.0 ± 16.7	73.5 ± 16.6	71.4 ± 17.0
	Contact	Lead	69.0 ± 16.8	62.3 ± 20.2	79.6 ± 18.3	79.7 ± 19.8	74.8 ± 19.3	79.5 ± 20.2	85.9 ± 18.2	83.1 ± 18.0
	Step 2	Rear	55.4 ± 18.3	53.4 ± 21.1	57.3 ± 19.4	57.8 ± 23.3	53.8 ± 19.4	61.9 ± 20.2	56.1 ± 22.5	57.2 ± 27.3
	Step 1	Rear	55.1 ± 18.6	50.4 ± 24.3	68.6 ± 19.1	59.0 ± 22.4	59.5 ± 16.7	58.8 ± 22.6	62.5 ± 22.1	63.1 ± 21.5
	Contact	Rear	52.6 ± 21.5	46.4 ± 29.5	75.3 ± 21.4	62.3 ± 26.8	66.5 ± 18.7	68.7 ± 26.2	69.7 ± 24.2	67.5 ± 27.8
Lumbopelvic flexion (+)/extension (–)	Step 2		13.7 ± 14.8	18.5 ± 21.3	18.8 ± 17.3	20.4 ± 17.5	20.3 ± 16.9	18.8 ± 20.4	16.8 ± 17.3	19.7 ± 18.5
	Step 1		16.2 ± 15.5	20.0 ± 20.3	22.4 ± 18.6	23.4 ± 17.9	24.7 ± 17.1	22.0 ± 20.5	20.9 ± 18.2	24.0 ± 20.0
	Contact		12.9 ± 14.0	18.6 ± 21.5	23.4 ± 18.4	24.7 ± 21.8	24.3 ± 18.2	22.7 ± 21.5	21.5 ± 19.2	24.6 ± 21.5
Thoracolumbar flexion (+)/extension (–)	Step 2		12.3 ± 13.4	9.3 ± 13.4	16.6 ± 14.8	18.1 ± 14.3	13.9 ± 14.5	14.8 ± 15.8	20.3 ± 15.4	20.1 ± 15.6
	Step 1		11.3 ± 13.0	6.0 ± 15.4	17.7 ± 13.3	19.6 ± 16.3	14.1 ± 11.7	9.7 ± 18.5	21.8 ± 13.3	19.6 ± 19.9
	Contact		9.3 ± 12.8	3.8 ± 14.4	16.3 ± 15.4	21.2 ± 15.2	15.7 ± 12.1	16.4 ± 15.3	23.6 ± 14.6	22.5 ± 18.8
Trunk–pelvis extension (+)/flexion (–)	Step 2		–30.0 ± 11.1	–32.4 ± 14.8	–39.2 ± 14.4	–42.0 ± 13.8	–38.7 ± 14.9	–38.8 ± 14.5	–40.3 ± 14.4	–43.5 ± 14.5
	Step 1		–29.2 ± 13.9	–31.3 ± 16.6	–42.9 ± 16.2	–45.8 ± 15.6	–42.4 ± 14.9	–39.3 ± 17.1	–45.4 ± 16.3	–48.2 ± 18.8
	Contact		–24.7 ± 11.9	–26.5 ± 18.7	–44.5 ± 15.1	–48.2 ± 19.3	–42.3 ± 14.4	–41.8 ± 18.0	–47.2 ± 16.3	–51.2 ± 19.5
Head extension (+)/flexion (–)	Step 2		–16.9 ± 12.7	–16.6 ± 11.8	–29.1 ± 13.3	–30.7 ± 12.2	–24.9 ± 12.6	–27.5 ± 12.0	–32.1 ± 13.9	–35.1 ± 14.0
	Step 1		–15.2 ± 13.0	–14.3 ± 12.2	–32.0 ± 13.2	–34.1 ± 12.5	–28.2 ± 12.5	–29.3 ± 12.4	–38.7 ± 14.5	–41.7 ± 13.3
	Contact		–12.2 ± 13.0	–9.8 ± 12.7	–40.4 ± 17.1	–44.7 ± 17.0	–36.3 ± 16.4	–35.4 ± 13.3	–53.3 ± 18.5	–54.4 ± 15.9

DOM, dominant-side shoulder engagement; ND, nondominant-side shoulder engagement.

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(i.e., DTS), and then the orange/red zone (i.e., SPL) and red zone (i.e., SNRL) with the lowest tackler head accelerations.

Dominant tackles have the highest head accelerations for the tacklers: recommended that, when tacklers execute dominant tackles, they contact the ball carrier mid, not hip area. Within a team's defensive strategy, a tackler will engage with the ball carrier's lower torso (i.e., green zone) to execute a "dominant tackle." A dominant tackle is defined when the ball carrier is moved backward and, by the completion of the tackle, is taken to the ground (13). This study suggests that the tackler's inertial head acceleration can be decreased when performing a dominant tackle by the tackler engaging at the mid (DTS; i.e., orange zone) rather than the lower (DNRL; i.e., green zone) torso of the ball carrier. By executing this slightly higher torso contact height at the midtorso, the tackler also adopts a more optimal "head-up and forward" gaze focus on the ball carrier before contact (i.e., less head flexion) as well as a straight back posture (i.e., less thoracolumbar flexion than in the DNRL technique). This DTS technique variant aligns better with coaching recommendations (42), as well as injury risk and tackle performance evidence associated with the head (42–44) and a straight back (44,45) posture.

Upright tackles increase the risk of head injury: how altering the way the tackler engages in contact with the ball carrier can reduce the injury risk in smother tackles. Applying an intervention to lower the legal height of the tackle in professional rugby has not been found to alter concussion incidence (9). The issue is that only considering one variable (i.e., tackle height) may be too simplistic, and the biomechanical characteristics of the tackle and the associated risk for concussion are far more complex. The present study finds that, for similar tackle heights (SNRL, SPL), the way the tackler was instructed to engage in contact with the ball carrier when executing a smother tackle can significantly alter the head impact. The upper (SNRL) and mid/upper (SPL) torso tackles performed in this study are often known as a "smother tackle," because tackler uses his chest for contact while wrapping his arms around the ball carrier (37). The SPL instruction significantly reduced peak head linear acceleration compared with the SNRL, DTS, and DNRL. This is important because linear head acceleration can still cause brain angular acceleration without angular head acceleration when a mild deceleration of the head is applied (46). When the tackler executes the SPL technique, a more optimal head-up and forward (i.e., less head flexion) and straight back posture (i.e., less thoracolumbar flexion, lumbopelvic flexion) was attained, compared with the SNRL technique.

Importantly, our mid/upper torso contacts in the SPL involved tacklers moving at relatively slow speeds and under careful instruction of an expert coach in a controlled environment. The point of contact between the tackler's chest/pectoral region and the ball carrier's body was approximately the height of the sternum (i.e., intersection between the mid and upper torso), not higher. The tackler started from a very low position and then executed a vertical pop-up action at the last moment. When engaging in contact, the tackler used his pectoral on the ball carrier's forearm and ball to wrap up both the arms around the ball carrier and then reorient the motion of the ball carrier into upward direction via the pop-up action. This tackle also then moves the ball carrier laterally instead of driving the ball carrier backward to allow defensive teammates to assist in the tackle. Most importantly, the tackler always positions his head outside the ball carrier shoulder when engaging in contact with the ball carrier.

These technical cues in contact height and the way the tackler engages in contact may be essential for the lower resultant head accelerations and also might reduce the tackler's risk of contact with high-risk body parts (head, elbow, and shoulders) of the ball carrier. These contact types, particularly head-to-head contacts during higher contact tackles when tacklers are upright, have been found to increase the risk of head injury (10,19,27,47). Therefore, there is a potential tradeoff between the slightly higher torso contact we find that reduces head acceleration in this study and the real-world risk of such higher contact tackles leading to high-risk head contacts and thus a greater risk as found in other studies.

Player speed. Ball carriers and tacklers typically engage in a tackle at a slow speed (define as walking or jogging into the tackle) (37), and the tackle speed was performed by both players in the current study. Whether the ball carrier or tackler approaches a front-on tackle with faster speed in elite rugby union remains contentious (48,49), because nearly half of the time the ball carriers are at a higher speed than the tackler (49). This study observed that the ball carriers ran significantly faster approaching the tackle and were faster at contact, despite standardizing approach distance between the players in an attempt to limit the confounding effect of player speed (10,34). This is likely to reflect the time required for the tacklers to set their body position and execute the chosen tackle technique, whereas the only focus of the ball carrier was to oppose the actions of the tackler. These demands on the tackler are likely to have also contributed to the player's speed differing between the various techniques, when approaching the tackle but not at contact. Both NRL torso instructions (SNRL, DNRL) were performed with a faster peak approach speed by the tackler than either variation of the tackling techniques (SPL, DTS), which is most likely a reflection of the familiarity of the traditional tackling technique rather than the variations in tackling techniques.

In contrast, in the traditional tackling types, the ball carrier approaches the tackler at a slower speed than in the tackling technique variants. These speed differences may contribute partly to our observed kinematic findings, particularly the reductions in head acceleration for the upper torso tackles, which were variations on the typical technique and thus performed at lower tackler speeds, potentially with greater caution and unfamiliarity. This may in turn have implications for real-world application, because the relatively faster speeds, higher intensities, and greater unpredictability of tackles during match play may change head kinematics for any given contact height and tackle technique. Further research may be required to confirm this possibility.

How a tackler modifies his body position to engage in different torso tackle heights is not reflected by his hip and knee flexion. Video analysis framework defines body position before contact as upright, medium, or low, differentiated by knee and hip flexion, and body height (38). This study found that knee flexion was similar across all four tackle techniques. Hip flexion did not differentiate when changing the torso tackle height (i.e., SNRL vs DNRL). The 3D definition of hip flexion in this study was thigh segment relative to the pelvis segment. This contrasts with the definition of hip flexion in 2D video analysis, where it is assessed by the thigh relative to the trunk (the pelvis and thorax treated as a single segment). When identifying how the tacklers executed the lower torso height in the DNRL technique compared with the SNRL technique, the tacklers did not alter their knee or hip flexion; however, tacklers increased their trunk–pelvis joint angle by lowering their trunk segment relative to the ground. In these participants, the tacklers only decreased their tackle height by increasing their trunk flexion, not their knee or hip flexion. As such, caution is warranted on how researchers quantify body position before and at contact.

Understanding linear versus angular head acceleration. Acceleration of the skull causes rapid deformation of brain matter that is thought to be the likely cause of concussion (46). This makes intuitive sense because the impulsive forces (incurred through a rapid acceleration and deceleration) applied either directly or indirectly to the head during a tackle transfer forces through the head to the brain. Those forces can result in a concussion by placing strain on tether points within the brain, which may lead to axonal stress, neuroinflammation, and a neurometabolic cascade (21). This study observed that head linear acceleration was significantly different between all tackling instructions, and angular acceleration only differed in the DNRL. Because of anatomical constraints of these tether points on the brain, when the skull decelerates, the brain's center of mass will continue to move but the tethering will cause the brain to rotate (46). This is why brain angular acceleration can occur with only linear acceleration of the skull when a mild deceleration of the head is applied (46), and thus, both head linear and angular accelerations are important to measure. Reducing the magnitude of inertial head kinematics of a single tackle or across hundreds of tackles will both achieve and make tackling safer regardless of either concussion injury mechanism of either an acute event (i.e., direct head impact) or subconcussive impacts (i.e., indirect head impact). Recent attempts have been made to accurately quantify and monitor a player's in-game exposure to direct and indirect head impacts in collisions sports via accelerometry (50,51). These devices use linear acceleration magnitude threshold of $>5g$ (52) or $\geq 10g$ (50,51,53) to identify an impact event. These thresholds are well above this current study's average peak linear acceleration magnitude reported but are not too dissimilar to a recent in-game study of professional rugby league players tackling (linear (median, $7.1g$; Q1, $5.2g$; Q3, $9.9g$) and angular acceleration (median, 0.6 krad·s^{-2}; Q1, 0.4 krad·s$^{2-1}$; Q3, 0.9 krad·s^{-2})). Caution is advised when comparing different methodological approaches of measuring (54) and filtering (24) head impact data (i.e., head inertial kinematics), and another confounding issue is the ambiguous threshold of head impact data (i.e., head inertial kinematics) that may cause concussion. It is recommended that future observational or interventional research investigating different tackle types measure both 3D head linear and angular accelerations using 3D motion capture and wearable sensors simultaneously to clarify our understanding of this relationship. The unsuccessful tackles are considered as a subset of all tackles in this study and should be the subject of future research to explore in detail if there is a risk that, when the tackler is deemed to incorrectly execute the tackle, it produces undesirable inertial head kinematics. This may have implications for the global head injury risk in dynamic situations where tacklers do make errors, and should be a subject of future research.

Limitations. Because of limitations to the current study, these results can only be considered as preliminary and require replication in larger sample sizes. Categorization of the unsuccessful tackles by the two experts and the expert coach potentially leading the participants when instructing the techniques in this study is likely to create a risk of bias because some tackling techniques may produce higher inertial head kinematics when unsuccessful. Future research should thus explore tackle success in different tackle types, with a focus on outcomes when tackles are unsuccessful.

Our findings may not translate to tackles involving more than one tackler, differing approach direction, playing position or experience, player skill level, age, or tackles that are completed by taking the ball carrier to ground. Furthermore, the artificial laboratory environment (as opposed to game environment) may have influenced the ball carrier's and the tackler's ability to perform the various tackle techniques. The study only investigated a slow tackle speed; therefore, it remains unknown if altering tackling speed before contact changes tackling technique. Furthermore, the experimental tackles were not completed to the ground, and that could further reduce the generalizability of findings to actual game play. The study design does not enable any further investigation of the durability of the behavioral modification (i.e., the robustness of the various tackle techniques) over longer periods of time, or the transfer of the behavioral modification to match play conditions. Injury history in the subjects was not recorded, so secondary analyses could not be conducted to determine if previous injury influenced any of the participants' motion.

CONCLUSIONS

Head inertial accelerations can be modified in a front-on, one-on-one tackle, at slow speed within a single session by instructing tacklers to change the torso contact height on the ball carrier and modifying the way they engage in player contact. The inclusion of a tackle-specific coaching instruction training program to alter the impulse forces to the head (i.e., head inertial kinematics) during the tackle may be a viable concussion reduction strategy.

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The results of the present study do not constitute endorsement by the American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

S. E. declares that she has no conflict of interest. A. G. serves as a scientific advisor for hitIQ, Ltd. He has a clinical practice in neuropsychology involving individuals who have sustained sport-related concussion (including current and former athletes). He has been a contracted concussion consultant to Rugby Australia (2016–2020). He has received travel funding or been reimbursed by professional sporting bodies, and commercial organizations for discussing or presenting sport-related concussion research at meetings, scientific conferences, workshops, and symposiums. He has received research funding from the NRL for the Retired Players Brain Health research program. Previous grant funding includes the NSW Sporting Injuries Committee; the Brain Foundation (Australia); an Australian–American Fulbright Commission Postdoctoral Award; a Hunter New England Local Health District, Research, Innovation and Partnerships Health Research & Translation Centre and Clinical Research Fellowship Scheme; and the Hunter Medical Research Institute, supported by Jennie Thomas, and the Hunter Medical Research Institute, supported by Anne Greaves. R. T. is a research consultant to World Rugby (Pty) Ltd, the governing body for Rugby Union globally. G. L. I. serves as a scientific advisor for NanoDx™ (formerly BioDirection, Inc.); Sway Operations, LLC; and Highmark, Inc. He has a clinical and consulting practice in forensic neuropsychology, including expert testimony, involving individuals who have sustained mild traumatic brain injuries (including athletes). He has received research funding from several test publishing companies, including ImPACT Applications, Inc.; CNS Vital Signs; and Psychological Assessment Resources, Inc. He has received research funding as a principal investigator from the National Football League, and salary support as a collaborator from the Harvard Integrated Program to Protect and Improve the Health of National Football League Players Association Members. C. R. L. serves as a consultant neurologist to the NRL providing a pro bono second opinion to current players regarding concussion assessment and management for the player's club doctor. G. S. has received pilot research funding from the Harvard Football Player's Health Study, funded through the National Football League Players Association. T. T. is employed by the National Rugby League School to Work Transition Officer.

REFERENCES

1. *World Rugby [Internet]*. Dublin (Ireland): World Rugby; [cited 2019 Oct 25]. Available from: https://resources.world.rugby/worldrugby/document/2020/07/28/212ed9cf-cd61-4fa3-b9d4-9f0d5fb61116/P56-57-Participation-Map_v3.pdf.
2. Fuller CW, Brooks JH, Cancea RJ, Hall J, Kemp SP. Contact events in rugby union and their propensity to cause injury. *Br J Sports Med*. 2007;41(12):862–7.
3. Gabbett TJ, Jenkins DG, Abernethy B. Physical collisions and injury in professional rugby league match-play. *J Sci Med Sport*. 2011; 14(3):210–5.
4. *NRL [Internet]*. Sydney (Australia): National Rugby League; [cited 2020 Nov 4]. Available from: https://www.nrl.com/stats/players/?competition=111&season=2019&stat=3.
5. Quarrie KL, Hopkins WG, Anthony MJ, Gill ND. Positional demands of international rugby union: evaluation of player actions and movements. *J Sci Med Sport*. 2013;16(4):353–9.
6. Fuller CW, Taylor A, Raftery M. Epidemiology of concussion in men's elite Rugby-7s (Sevens World Series) and Rugby-15s (Rugby World Cup, Junior World Championship and Rugby Trophy, Pacific Nations Cup and English Premiership). *Br J Sports Med*. 2015;49(7):478–83.
7. Gardner AJ, Iverson GL, Williams WH, Baker S, Stanwell P. A systematic review and meta-analysis of concussion in rugby union. *Sports Med*. 2014;44(12):1717–31.
8. Gardner A, Iverson GL, Levi CR, et al. A systematic review of concussion in rugby league. *Br J Sports Med*. 2015;49(8):495–8.
9. Stokes KA, Locke D, Roberts S, et al. Does reducing the height of the tackle through law change in elite men's rugby union (The Championship, England) reduce the incidence of concussion? A controlled study in 126 games. *Br J Sports Med*. 2021;55(4):220–5.
10. Cross MJ, Tucker R, Raftery M, et al. Tackling concussion in professional rugby union: a case-control study of tackle-based risk factors and recommendations for primary prevention. *Br J Sports Med*. 2019;53(16):1021–5.
11. Kemp S, West S, Anstiss T, et al. [Internet]. Available from: https://www.englandrugby.com/participation/playing/player-welfare-rugby-safe/rugbysafe-research. Accessed April 30, 2021.
12. Fuller C, Taylor A, Douglas M, Raftery M. Rugby World Cup 2019 injury surveillance study. *S Afr J Sports Med*. 2020;32(1):1–6.
13. King D, Hume PA, Clark T. Nature of tackles that result in injury in professional rugby league. *Res Sports Med*. 2012;20(2):86–104.
14. *NRL [Internet]*. Sydney (Australia): National Rugby League; [cited 2020 May 12]. Available from: https://www.playrugbyleague.com/media/2967/tacklesafe-deliverer-guide.pdf.
15. Quarrie K, Gianotti S, Murphy I, Harold P, Salmon D, Harawira J. RugbySmart: challenges and lessons from the implementation of a nationwide sports injury prevention partnership programme. *Sports Med*. 2020;50(2):227–30.
16. Viljoen W, Patricios J. BokSmart—implementing a National Rugby Safety Programme. *Br J Sports Med*. 2012;46(10):692–3.
17. Fraas MR, Burchiel J. A systematic review of education programmes to prevent concussion in rugby union. *Eur J Sport Sci*. 2016;16(8): 1212–8.
18. Tierney GJ, Simms CK. Can tackle height influence head injury assessment risk in elite rugby union? *J Sci Med Sport*. 2018;21(12):1210–4.
19. Gardner AJ, Iverson GL, Edwards S, Tucker R. A case–control study of tackle-based head injury assessment (HIA) risk factors in the National Rugby League. *Sports Med Open*. 2021;7(1):84.
20. Gardner AJ, Iverson GL, Quinn TN, et al. A preliminary video analysis of concussion in the National Rugby League. *Brain Inj*. 2015; 29(10):1182–5.
21. Giza CC, Hovda DA. The new neurometabolic cascade of concussion. *Neurosurgery*. 2014;75(4 Suppl):S24–33.
22. Walter AE, Wilkes JR, Arnett PA, et al. The accumulation of subconcussive impacts on cognitive, imaging, and biomarker outcomes in child and college-age athletes: a systematic review. *Brain Imaging Behav*. 2022;16(1):503–17.
23. McNabb C, Reha T, Georgieva J, Jacques A, Netto K, Lavender AP. The effect of sub-concussive impacts during a Rugby tackling drill on brain function. *Brain Sci*. 2020;10(12):960.
24. Edwards S, Lee R, Fuller GW, et al. 3D biomechanics of rugby tackle techniques to inform future rugby research practice: a systematic review. *Sports Med Open*. 2021;7(1):39.
25. Tierney GJ, Richter C, Denvir K, Simms CK. Could lowering the tackle height in rugby union reduce ball carrier inertial head kinematics? *J Biomech*. 2018;72:29–36.
26. Tierney GJ, Simms C. Predictive capacity of the MADYMO multibody human body model applied to head kinematics during rugby union tackles. *Appl Sci*. 2019;9(4):726.
27. Tucker R, Raftery M, Kemp S, et al. Risk factors for head injury events in professional rugby union: a video analysis of 464 head injury events to inform proposed injury prevention strategies. *Br J Sports Med*. 2017;51(15):1152–7.
28. Kawasaki T, Tanabe Y, Tanaka H, et al. Kinematics of rugby tackling: a pilot study with 3-dimensional motion analysis. *Am J Sports Med*. 2018;46(10):2514–20.

29. Faul F, Erdfelder E, Lang A-G, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–91.
30. Edwards S, Tahu T, Buchanan M, Tucker R, Fuller G, Gardner AJ. Can prior instruction successfully alter the tackle type executed by a player? *Int J Sports Sci Coach*. 2021;16(4):944–56.
31. *NRL [Internet]*. Sydney (Australia): National Rugby League; [cited 2020 May 12]. Available from: https://www.playrugbyleague.com/media/3179/nrl-coaching-manual-2019.pdf.
32. Seminati E, Cazzola D, Preatoni E, Trewartha G. Specific tackling situations affect the biomechanical demands experienced by rugby union players. *Sports Biomech*. 2017;16(1):58–75.
33. Usman J, McIntosh AS, Fréchède B. An investigation of shoulder forces in active shoulder tackles in rugby union football. *J Sci Med Sport*. 2011;14(6):547–52.
34. Tierney GJ, Lawler J, Denvir K, McQuilkin K, Simms CK. Risks associated with significant head impact events in elite rugby union. *Brain Inj*. 2016;30(11):1350–61.
35. Quarrie KL, Hopkins WG. Tackle injuries in professional rugby union. *Am J Sports Med*. 2008;36(9):1705–16.
36. Stokes KA, Locke D, Roberts S, et al. Does reducing the height of the tackle through law change in elite men's rugby union (The Championship, England) reduce the incidence of concussion? A controlled study in 126 games. *Br J Sports Med*. 2019;55(4):220–225.
37. Fuller CW, Ashton T, Brooks JH, Cancea RJ, Hall J, Kemp SP. Injury risks associated with tackling in rugby union. *Br J Sports Med*. 2010;44(3):159–67.
38. Hendricks S, Till K, den Hollander S, et al. Consensus on a video analysis framework of descriptors and definitions by the Rugby Union Video Analysis Consensus group. *Br J Sports Med*. 2020;54(10):566–72.
39. Schaefer A, O'Dwyer N, Ferdinands RED, Edwards S. Consistency of kinematic and kinetic patterns during a prolonged spell of cricket fast bowling: an exploratory laboratory study. *J Sports Sci*. 2018;36(6):679–90.
40. Winter DA. *Biomechanics and Motor Control of Human Movement*. Hoboken (NJ): John Wiley & Sons; 2009.
41. Burnham KP, Anderson DR. Multimodel inference: understanding AIC and BIC in model selection. *Sociol Methods Res*. 2004;33(2):261–304.
42. Hendricks S, O'Connor S, Lambert M, et al. Video analysis of concussion injury mechanism in under-18 rugby. *BMJ Open Sport Exerc Med*. 2016;2(1):e000053.
43. Hendricks S, Matthews B, Roode B, Lambert M. Tackler characteristics associated with tackle performance in rugby union. *Eur J Sport Sci*. 2014;14(8):753–62.
44. Tierney GJ, Denvir K, Farrell G, Simms CK. The effect of tackler technique on head injury assessment risk in elite rugby union. *Med Sci Sports Exerc*. 2018;50(3):603–8.
45. Tierney GJ, Denvir K, Farrell G, Simms CK. The effect of technique on tackle gainline success outcomes in elite level rugby union. *Int J Sports Sci Coach*. 2018;13(1):16–25.
46. Bayly PV, Cohen TS, Leister EP, Ajo D, Leuthardt EC, Genin GM. Deformation of the human brain induced by mild acceleration. *J Neurotrauma*. 2005;22(8):845–56.
47. Tucker R, Raftery M, Fuller GW, Hester B, Kemp S, Cross MJ. A video analysis of head injuries satisfying the criteria for a head injury assessment in professional Rugby Union: a prospective cohort study. *Br J Sports Med*. 2017;51(15):1147–51.
48. Hendricks S, Karpul D, Nicolls F, Lambert M. Velocity and acceleration before contact in the tackle during rugby union matches. *J Sports Sci*. 2012;30(12):1215–24.
49. Hendricks S, Karpul D, Lambert M. Momentum and kinetic energy before the tackle in rugby union. *J Sports Sci Med*. 2014;13(3):557–63.
50. Siegmund GP, Guskiewicz KM, Marshall SW, DeMarco AL, Bonin SJ. Laboratory validation of two wearable sensor systems for measuring head impact severity in football players. *Ann Biomed Eng*. 2016;44(4):1257–74.
51. King D, Hume PA, Brughelli M, Gissane C. Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches. *Am J Sports Med*. 2015;43(3):614–24.
52. Tooby J, Weaving D, Al-Dawoud M, Tierney G. Quantification of head acceleration events in Rugby League: an instrumented mouthguard and video analysis pilot study. *Sensors (Basel, Switzerland)*. 2022;22(2):584.
53. Goodin P, Gardner AJ, Dokani N, et al. Development of a machine-learning-based classifier for the identification of head and body impacts in elite level australian rules football players. *Front Sports Act Living*. 2021;3:725245.
54. Tierney G. Concussion biomechanics, head acceleration exposure and brain injury criteria in sport: a review. *Sports Biomech*. 2021:1–29.