

A game for all shapes and sizes? Changes in anthropometric and performance measures of elite professional rugby union players 1999– 2018

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ABSTRACT

Background Rugby union player size has increased since the game turned professional in 1995. Changes in physical and performance capability over this period have yet to be fully described.

Hypothesis Increases in player momentum would result from changes in body mass.

Methods Within-player rates of change in anthropometric and kinetic variables with season played were sampled in three successively studied professional rugby union club cohorts playing at the highest level of European competition between 1999 and 2019. Data comprised 910 seasons of observation for 291 elite male players. Most players had 2, 3 or 4 seasons of observation. Mixed-effects modelling distinguished changes independent of position played, club and international status.

Results With each season played, player body mass, fat-free mass and maximum speed increased significantly, while per cent fat decreased. The mean maximal velocity of a rugby player in 1999 was 8.2 (± 0.18) m/s, which in 2019 had risen to 9.1 (± 0.10) m/s. Player's momentum in 2019 was 14% more than those playing in 1999. In the Front Five, momentum increased in this period by >25%, mainly driven by greater running speed, disproving our hypothesis.

Conclusions The momentum of players, particularly forwards, increased markedly over 20 seasons of professional rugby. The resulting forces generated in collisions are thus significantly greater, although these may be mitigated by better player conditioning. Proactive regulation to address player safety may be required to address the changing nature of anthropometric measures and physical performance, minimising injury rates and potential long-term sequelae.

INTRODUCTION

Since elite rugby union became professional in 1995, an off-the-field 'arms race' has ensued whereby professional coaches, physical conditioners and medical staff now provide elite quality training, facilities and nutrition to maximise physical performance.¹ In the 25

Key messages

What is already known on this topic

- The body mass of rugby players has increased since the game became professional.

What this study adds

- Over 20 seasons of elite professional rugby union, players have gained body mass and lean mass, and increased their maximal running speed.
- Players' overall momentum has increased by 14%; the Front Five players' momentum has increased by 25%, driven mainly by increased running speed.

How this study might affect research, practice or policy

- Increased momentum of professional rugby players may lead to greater injury frequency and severity, raising concerns about player welfare.

years of professional play, the elite level of the game is remarkable for the physical size of players.^{2 3} Many studies have shown longitudinal anthropometric changes occurring in various playing cohorts.^{1 4–8} Questionnaire surveys of former players suggest that the average professional rugby career lasts 7–9 years.^{9 10}

The rules of the game of rugby have evolved during this period, including allowing competition for the ball on the ground after a tackle and increasing the number of substitutions permitted to eight.¹¹ These rule changes have enabled teams to select larger players who can compete physically and introduce fresh players when these bigger players tire.¹² This means cardiovascular endurance fitness has become less important, allowing more large muscular players within the starting squad to replace one another throughout the match.¹² Some studies have hypothesised that law changes in the game have directly impacted the players' physical developments.^{2 3} How

these physical changes develop, and in what areas, are of interest to project the development of the game and the standards which players of the future might aim for, as well as carrying significant repercussions for acute and long-term player safety.^{13–16} Descriptions of players' physical changes may inform re-appraisal of aspects of the game that may be associated with a risk to player welfare, as well as maintaining the game as an entertaining spectacle where skill, speed and strategy play as much of a part as size.

We aimed to assess the longitudinal changes in mass, velocity, momentum and peak kinetic energy using two decades of standardised elite and international rugby player data.

METHODS

This was an observational study with measures repeated in successive seasons for most players. Male rugby union players employed by three professional rugby union clubs were represented, with data collected over 20 years from the 1999–2000 season to the 2018–2019 season. Each team played at the highest level of European club rugby during the specified timeframe. One squad's data were collected from 1999 to 2003, the next from 2004 to 2013 and the third from 2014 to 2019. Players' anthropometric (body mass and composition) measures were recorded, and physical capability (maximal running speed) was assessed.

Players

All players were in the men's senior squad for at least one season at each club. All participants were at least 17 years old. A cohort of 291 players was analysed; 66 at club 1 (1999–2003), 143 at club 2 (2004–2013) and 82 at club 3 (2013–2019). Of these, 130 (69 forwards and 61 backs) had played international-level rugby, and 161 (94 forwards and 67 backs) remained at elite club level.

MEASUREMENTS

Body mass (Seca scales, Hamburg, Germany; accuracy 0.1 kg) was measured up to five times per week at training, and the weekly mean body mass was recorded. The mean of each weekly score was used to determine a seasonal mean body mass. Body mass measurements were standardised with players measured in a fasted state in the morning, unshod, wearing shorts and a lightweight top.

Body composition was determined by skinfold thickness measured with calibrated Harpenden callipers (Body Care, Kenilworth, UK), as described in the Anthropometric Standardisation Reference Manual.¹⁷ All measurements were undertaken by personnel accredited by the International Society for the Advancement of Kinanthropometry. Subcutaneous fat mass was calculated using the Jackson and Pollock 7-site (chest, mid-axilla, suprailiac, abdomen, thigh, triceps and subscapula) skinfold test performed monthly between 1999 and 2006 but then twice per month from 2006 onwards.¹⁸ The mean score from each season was calculated. Fat-free mass was

obtained by subtracting the derived fat mass from the body mass.

Maximal running speed was determined from a 40 m straight-line shuttle sprint test between 1996 and 2005. This test was conducted under strict indoor testing conditions using timing light gates (Brower Timing Systems, Draper, Utah, USA) with light beam gates situated at 0 m, 10 m and 40 m. Speed was calculated using the time taken to complete 30 m (from the 10 m gate to the 40 m gate) and converted into metres per second. These tests were typically conducted three or four times per season. Multiple variables affect the maximal speed in training scenarios, including (but not limited to) wind speed and direction and the player's training load immediately before testing. Each player's maximal speed at any point during each season was recorded as the score. Mean values were not used because of the effects of external factors described above and relatively infrequent testing.

From 2006 onwards, Global Positioning Satellite (GPS) (Catapult, Melbourne, Australia) systems became the standard for appraising player speeds within the elite rugby fraternity. Maximal speeds could thus be determined from any training session regardless of location, surface or weather conditions. GPS has been shown to reliably and accurately measure running speed in rugby players.¹⁹

Momentum was calculated as the product of player body mass (in kg) and maximum speed (in m/s) and expressed in kilogram metre per second (kg·m/s).

Kinetic energy was calculated from the equation $\frac{1}{2}mv^2$, where *m* is player body mass (in kg) and *v* is the velocity (in m/s) and expressed in Joules (J).

Distance covered during competitive matches was determined from GPS devices worn under or within players' shirts, starting in 2011. Each season the mean distance covered in matches was calculated for each player. To correct for players who were substituted (tactically or due to injury), the match-play distance was calibrated to a full 80 min play. For example, if a player covered 5000 m and was substituted after 60 min, their '80 min distance' was calculated as:

$$((1 - 60/80) \times 5000) + 5000 = 6250 \text{ m}$$

When players were on the pitch for <50 min, this measure was prospectively not included; when players were sin-binned (off the pitch for 10 min as punishment for infringements) or temporarily removed from the field of play to undergo head injury assessment, this time was accounted for as described above.

Statistical methodology

To analyse the data, we divided the players into groups according to playing position, namely: Front Five (FF; props, hookers, second rows), Back Row (BR; flankers and number 8), Half-Backs (HB; scrum-half and fly-half/stand-off/first five-eighth), Back Five (BF; centres, wings, full backs). Each player's first season of observation was then taken as their baseline. Data were analysed

using STATA V.13 for Windows (Stata, College Station, Texas, USA). Continuous variables were summarised as medians (IQR). Categorical variables were summarised as percentages. Significant variation between groupings was evaluated for continuous variables using Kruskal-Wallis one-way analyses of variance and for categorical variables by χ^2 tests. Players varied in the number of seasons for which data were recorded; therefore, changes in anthropometric and performance measures with seasons played were evaluated using mixed model regression analysis with individual ID number as grouping variable (STATA command: 'mixed'). Mixed model analysis was also used to evaluate interactions between the number of seasons played and position, club and international status in the changes in anthropometric and performance measures observed.

RESULTS

We analysed anthropometric and performance data of 291 professional rugby union players over a 20-season period from 1999 to 2019. For the first data collection, the mean (SD) age was 24.0 (\pm 3.7) years. Of these, 227 (78%) had between 2 and 11 seasons of observations recorded. There was no significant difference in initial age between the four groups of players by position: FF 24.1 (\pm 3.7 years), BR 23.2 (\pm 4.0) years, HB 24.5 (\pm 3.4) years, BF 24.0 (\pm 3.6) years; $p=0.36$.

The distribution of players within each playing group was not significantly different between the three clubs ($p=0.79$). Likewise, the proportions of elite professional or international players represented in the data did not differ between clubs ($p=0.69$), nor was there a difference in elite professional or international status by position played ($p=0.32$).

There was a highly significant variation by position in every anthropometric and performance measure (table 1). Not unexpectedly, forwards were heavier than backs, with FF heaviest and HB lightest of the playing groups. Likewise, backs were faster than forwards at baseline. With each successive season played, players became bigger, leaner and faster; body mass, fat-free mass, maximum speed and momentum increased significantly, and per cent fat decreased (table 2). Body fat decreased from 15.4% (\pm 0.0) in 1999 to 12.3% (\pm 0.0) in 2019. The mean maximal velocity of a rugby player in 1999 was 8.2 (\pm 0.18) m/s, which in 2019 had risen to 9.1 (\pm 0.10) m/s. Momentum, the product of mass and speed, increased by >12 kg·m/s each season. The momentum of players in 2019 was 14% more than those playing in 1999 across all player cohorts; in the FF, the increase in this period was >25%.

Finally, we grouped seasons in 4-year blocks (aligned with the Rugby World Cup cycle) and found similar results in anthropometric (figure 1) and performance parameters (figure 2A,B). Distance covered increased for all player groups except BR, with the backs covering most distance.

Table 1 Player baseline characteristics by position (median (IQR))

	All players	N	Front Five (n=115)	Back Row (n=47)	Half-Backs (n=45)	Back Five (n=82)	Kruskal-Wallis p value
Body mass (kg)	104.0 (92.1, 115.0)	289	116 (113, 121)	108.0 (103, 110)	88.3 (83.3, 91.0)	94.0 (88.5, 99.2)	<0.001
Per cent fat (%)	13.8 (11.7, 16.8)	286	17.1 (14.8, 18.6)	14.6 (12.7, 16.5)	12.1 (10.2, 13.1)	11.7 (10.6, 12.8)	<0.001
Fat-free mass (kg)	88.8 (81.6, 95.6)	283	95.6 (92.1, 100.4)	92.2 (88.5, 95.4)	77.6 (74.6, 80.1)	83.5 (78.4, 98.0)	<0.001
Maximum speed (m/s)	8.8 (7.7, 9.3)	281	7.5 (7.0, 8.0)	8.6 (8.3, 8.8)	9.3 (9.0, 9.5)	9.4 (9.2, 9.6)	<0.001
Momentum (kg·m/s)	869 (818, 920)	280	852 (803, 914)	920 (874, 948)	819 (771, 839)	883 (831, 920)	<0.001
Kinetic energy (J)	3730 (3326, 4101)	280	3233 (2856, 3619)	3882 (3640, 4143)	3736 (3556, 3901)	4118 (3921, 4422)	<0.001
Distance covered (m/game)*	6591 (6213, 7111)	83	6199 (5998, 6425)	6487 (6213, 6637)	7169 (6889, 7353)	7150 (6879, 7389)	<0.001

*n=83, 35, 11, 11 and 26, respectively.

Table 2 Mixed-effects model-derived change in characteristic per season played (coefficient (95% CI))

	Change per season (904 observations for 291 players)	P value
Body mass (kg)	+0.512 (0.406 to 0.618)	<0.001
Per cent fat (%)	-0.408 (-0.475 to -0.341)	<0.001
Fat-free mass (kg)	+0.896 (0.772 to 1.020)	<0.001
Maximum speed (m/s)	+0.063 (0.045 to 0.082)	<0.001
Momentum (kg·m/s)	+12.1 (9.6 to 14.6)	<0.001
Kinetic energy (J)	+77.5 (60.4 to 94.6)	<0.001
Distance covered (m/game)*	+11.4 (-6.4 to 29.3)	0.2

*344 observations for 142 players.

BR players had the greatest momentum at each time point (figure 2C). In particular, FF players had a large gain in momentum for the seasons 2015–2018 compared with the previous four seasons 2011–2014 (961.9±79.2 vs 888.1±70.8 kg·m/s). This appears to be mostly due to gain in speed in FF players (rather than increased body mass). When comparing the first four seasons combined (1999–2002) and the last four seasons (2015–2018) data, body mass of the BF increased by 4%, HBs decreased by 0.5%, BR increased by 2.6% and FF by 3.8%. However, when investigating changes in speed over the same timelines, the maximum speed of BF increased by 2.2%, that of HB and BR by 5.0% and the top speed of BR by 11.5%. Momentum increased across all 20 seasons, whether baseline data or all readings from each player, were considered (online supplemental figure 1).

Players capped at full international level had less percentage body fat, were faster with greater momentum and kinetic energy and covered more distance than those who played at club level (table 3).

With each season played, in both international and club professional players, per cent fat decreased significantly, and body mass, muscle mass, speed, momentum and kinetic energy increased significantly (table 4). The rates of change per season appeared consistently less in international players than club professionals. Mixed-effects model analysis of these apparent interactions between international status and rate of change in anthropometric and performance indicators revealed that, in international players, per cent fat decreased per season by 0.161% less than in club professionals (p=0.02). At borderline significance, in international players, muscle mass increased by 0.250 kg less than in club professionals (p=0.05).

These analyses were repeated with data stratified according to the position played, with ‘forwards’ distinguished as the FFs and BR and ‘backs’ as the HB and BF. These analyses showed that the lower rate of decline in per cent fat and the lower rate of increase in muscle mass in international players was restricted to the forwards. Per cent fat decreased per season in international forwards by 0.22% less than in club professionals (p=0.01) and muscle mass increased by 0.33 kg less (p=0.05) in international forwards.

Among the backs, the only difference between international and club professional players in the rate of change with season played in anthropometric and performance measures was a reduction in distance covered per season in international players compared with an increase in club professionals. In international backs, the distance covered was 75.4 m less per season than club professional backs (p=0.039).

Grouped in 4-year blocks of seasons, international backs had a mean momentum of around 890 kg·m/s with little variation. Club-level backs maintained a significantly lower momentum of around 830 kg·m/s until the final quintile (2015–2018), when they matched the international players (online supplemental figure 2).

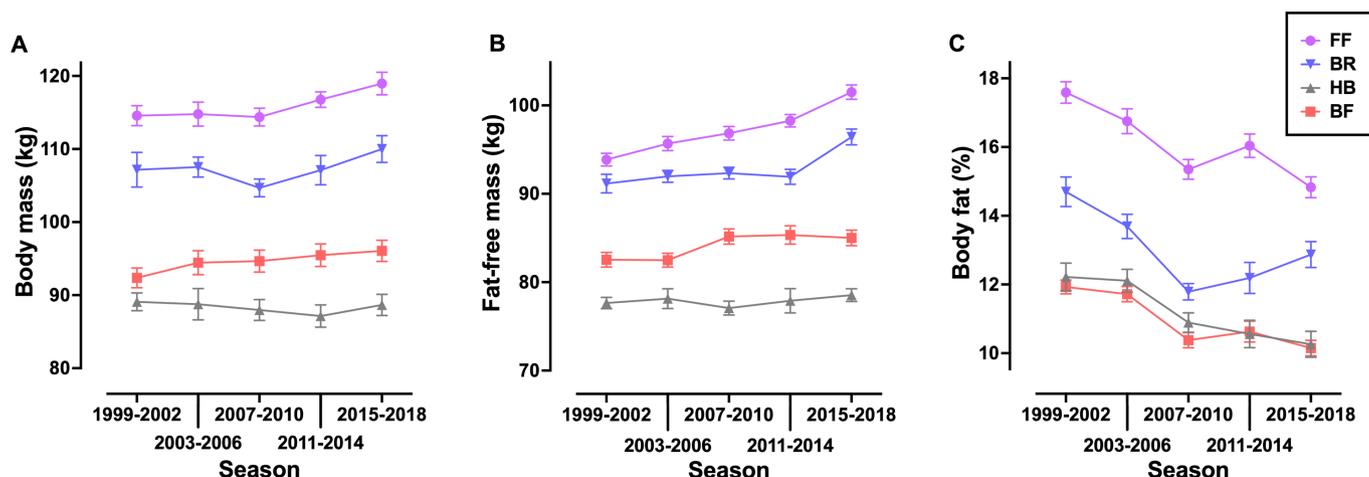


Figure 1 Anthropometric data of professional rugby players grouped into 4-year quintiles. Mean body mass (A) n=289. Fat-free mass (B) n=283. Body fat (C) n=286. BF, Back Five; BR, Back Row; HB, Half-Backs; FF, Front Five.

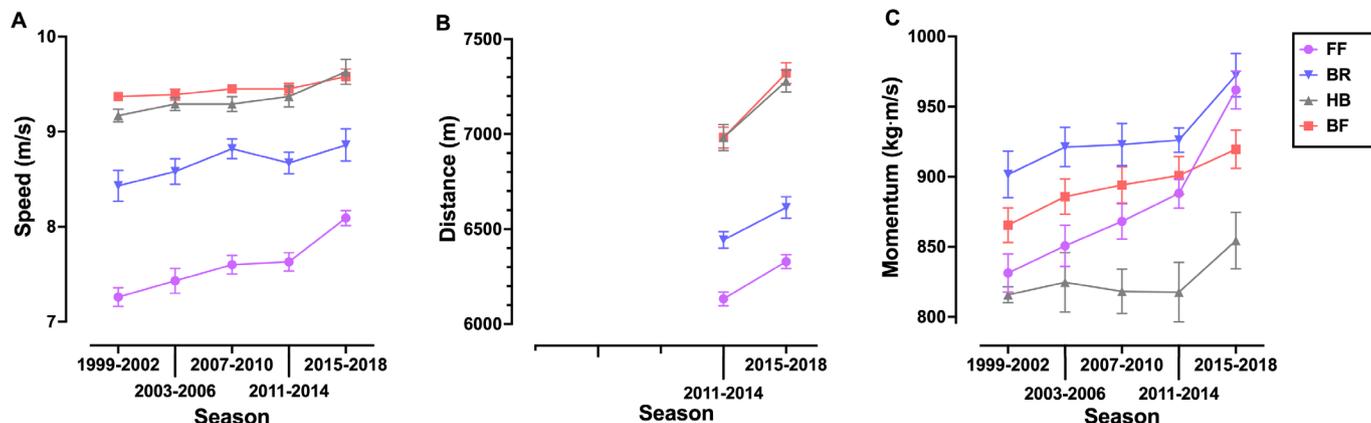


Figure 2 Performance and momentum data of professional rugby players grouped into 4-year quintiles. Maximum speed (A) n=291 players; distance covered (B) n=83 players and momentum (C) n=280 players. BF, Back Five; BR, Back Row; HB, Half-Backs; FF, Front Five.

DISCUSSION

We previously described significant increases in the body mass of northern hemisphere international rugby union players following the game turning professional. We stated that while players were able to increase their body mass, we hypothesised that they would be unable to increase their running speed significantly.⁴ In this paper, we describe changes in anthropometric and performance measurements in professional rugby union players for 20 seasons, commencing in 1996 when the game became fully professional.

Anthropometric measurements

Body mass increased significantly over time in our cohort of professional players, driven by clubs' developing professional infrastructure and supported by the laws of the game. Others have described similar increases in body mass in professional and elite youth rugby players over time.^{2 3 20} Interestingly, this gain in mass was most noticeable among forwards. In particular, the FF players, on average, gained 6.9 (± 3.0) kg. There were smaller increases in BR players and little or no change in either group of backs. Fluctuation in fat mass also occurred over the course of 20 seasons; strikingly though, the trend is of significant reductions in per cent body fat which appears

not to have fully plateaued. Thus, even players who did not gain total body mass will have lost fat and thus gained lean body mass. This is confirmed by large increases in fat-free mass (which can be roughly equated to muscle mass) in both forward groups.

Performance measurements

At all levels of rugby, acceleration and running speed remain sought-after qualities. Traditionally, the outside backs have traded on speed and have increased body mass to reinforce this advantage in recent years.^{2 3} Our data show that while the BF players remain the fastest on the pitch, the FF forwards have gained body mass and significantly increased their speed, thus disproving our initial hypothesis. This was based on our erroneous assumption that players peak speeds had already largely plateaued. Between 1999 and 2018, the time for the men's 60m sprint record improved by 1.1%, whereas elite rugby players' maximal speed increased by nearly 10% in the same timeframe.

Distance covered did not significantly increase overall; however, positional increases in the backs and FF players occurred. The distances recorded in this dataset are larger than those published from Super 14 rugby matches in the 2008 and 2009 seasons (between 4218 m

Table 3 Player baseline characteristics by international status (median (range))

	International (n=130)	Elite professional (n=161)	Kruskal-Wallis p value
Body mass (kg)	103.0 (94.0, 115.0)	105.0 (91.3, 115.0)	0.6
Per cent fat (%)	13.1 (11.2, 15.8)	14.2 (12.2, 17.0)	<0.001
Muscle mass (kg)	89.2 (82.1, 96.3)	88.6 (79.7, 94.9)	0.1
Maximum speed (m/s)	9.0 (7.6, 9.4)	8.6 (7.7, 9.2)	<0.001
Momentum force (kg·m/s)	879 (834, 927)	849 (807, 913)	<0.001
Kinetic energy (J)	3796 (3397, 4182)	3704 (3258, 4023)	<0.001
Distance covered (m/game)*	6793 (6304, 7185)	6448 (6108, 6943)	<0.001

*n=47 and 36, respectively.

Table 4 Change per season in characteristics by international status (coefficient (SE) p for coefficient)

	International (490 observations for 130 players)	Club professional (n=414 observations for 161 players)
Body mass (kg)	+0.483 (0.067) ^{<0.001}	+0.552 (0.088) ^{<0.001}
Per cent fat (%)	-0.316 (0.036) ^{<0.001}	-0.539 (0.062) ^{<0.001}
Muscle mass (kg)	+0.763 (0.070) ^{<0.001}	+1.09 (0.114) ^{<0.001}
Maximum speed (m/s)	+0.053 (0.011) ^{<0.001}	+0.077 (0.015) ^{<0.001}
Momentum force (kg·m/s)	+10.8 (1.49) ^{<0.001}	+14.0 (2.16) ^{<0.001}
Kinetic energy (J)	+68.3 (10.5) ^{<0.001}	+91.4 (14.9) ^{<0.001}
Distance covered (m/game)	-3.65 (11.7) ^{0.7}	+27.3 (16.4) ^{0.09}

*n=180 observations for 69 players and 164 observations for 73 players, respectively.

and 6389m depending on position).²¹ Data from 763 players who played for or against New Zealand between 2004 and 2010 also demonstrated positional differences, with backs covering more distance with ball in play, and at higher speeds.²² Backs total distance (5700–6300 m) was greater than forwards (5400–5700 m) but it was noted that forwards sustained notably more collisions.²² Some of this variance may relate to the methodology used (time-motion analysis of video recordings). In 2009, GPS data were published on two professional players taking part in matches in the UK and reported similar distances covered for the forward and back who were studied compared with our data.²³ In 2012, forwards in European Cup fixtures covered 4906m and backs 5959m, and in Japanese professional rugby in 2013–2014, a mean distance of 6041m was covered.^{24 25} More recently, the distance covered in age-grade matches in the UK and university rugby in South Africa highlights the difference in fitness levels between youth/university-level sport and professional rugby.^{26 27} Our data suggest increases in aerobic capacity, such that players can continue to run for longer or cover more distance earlier in the game.

Momentum

The combination of increased player mass and maximal velocity has seen the concept of momentum rise as a variable of importance in a sport that values contact.^{28 29} Momentum, a vector force, has seen steady growth for the 20 seasons studied, most markedly in the forwards. In the context of the large number of collisions that occur during a game (0.7–0.9 per min for forwards, 0.3–0.4 per min for backs), greater momentum may make the chance of ‘winning’ contact situations and provide a significant advantage to the team. However, this effect may be negated if the opposing team has equivalent gains in momentum.³⁰ Kinetic energy is less well reported and is not directional, as momentum is. Kinetic energy is more affected by changes in velocity than mass. Ranking player groups (by position), BR and BF players have greater momentum and kinetic energy than the front row and HB (kinetic energy: BF>BR>HB>FF and momentum: BR>BF>FF>HB).

In rugby league, momentum is greater in first division (national) than second division (state) players.³¹ While this could be because first division players are coached to achieve greater momentum after selection for the different attribute(s), it has been suggested that momentum may be a valid talent identification metric capable of highlighting players able to succeed at the highest levels. Momentum increases with age in academy rugby union players (under 16, under 18 and under 21) to a peak of 810±93kg·m/s in the older group.^{10 32 33} There is also an indication that momentum may have been used as a metric for talent identification; rugby league youth academy players who become professional players have (along with other physical attributes) greater momentum than those who do not.^{10 32 34} Additionally, university students who went on to become professional rugby union players did not have significantly greater momentum (in both forwards and backs) than those who did not (personal correspondence, based on the study by Hamlin *et al*).³⁵ While it is recognised that rugby union, rugby league and American football players have collectively gained body mass, it should also be understood that individuals frequently gain mass during their careers.^{20 36} Recognising that, in general, heavier players are slower than lighter players, optimising players’ body mass and, where possible, speed according to the position they play in, their skills, and the tactical intent of the team presents a challenge to both players and coaches.

International and club players

Momentum and kinetic energy were initially greater in international players. Interestingly, the momentum of international backs did not change over the study period; where previously they held a statistical advantage over their less forceful club-level teammates, this difference no longer exists, suggesting a degree of catch-up by the club-level players. Likewise, the momentum of international-level and club-level forwards has been equally matched for >10 years. It is important to recognise that the observed changes between international and club players are small, nuanced and may not translate to real-world effects. Thus, momentum may differentiate

academy from school adolescent rugby players, but in established professionals, it cannot discriminate between international and club players.⁸ This suggests that other factors beyond the force of impact determine selection at the international level; these may include sporting intelligence, strength, agility, individual skills (tackling, passing, kicking), teamwork and leadership. There is, for most, a threshold below which people are physically unsuited to professional rugby, however once at or above that level, being big and fast will only get you so far.

Implications of findings

The changing nature of anthropometry and performance metrics leads to significant concerns over player safety, law-making and adherence, consideration of training strategies.^{13–16}

Substitution laws

Up to eight tactical substitutions are allowed in rugby union; this generates a performance environment whereby players can be substituted if their performance falls, allowing further fresh players to enter the field of play to compete against fatigued players. In a game where the number of collision events (tackles and rucks) per fixture has increased from 139 at the 1999 Rugby World Cup to 211 in 2019, and the number of ball carries gone up by 27% in the same timeframe, this is of particular relevance given the current concerns for player welfare.³⁷ The risk of tackle injury is nearly doubled in professional players relative to players from lower tiers of the game.³⁸ FF forwards are the most likely to be substituted (often after about an hour of a match) and are those who have the greatest momentum along with the BR. Notwithstanding the legal action being prosecuted by a group of former players diagnosed with dementia linked to repeated head injuries and early retirements due to injury, World Rugby has made rule changes (around tackle height) to reduce the number of concussive and subconcussive injuries sustained. Anthropometric changes as a possible cause or risk factor for injuries sustained in tackle situations were not discussed in a recent narrative review. Still, it was noted that these injuries, typically the most severe, occur relatively more frequently towards the end of the match attributed to fatigue affecting tackle technique.³⁸ While it is feasible that better player conditioning for contact could mitigate some of the effects of increased momentum on injuries, the current substitution laws enable mismatches which may increase the risk of mistimed or misplaced collisions, especially later in the game. An open letter from the Progressive Rugby organisation has directly called substitutions to be used for injury only (<https://progressiverugby.org/>). This ensures that all players on the pitch measure their energy expenditure, expecting to complete 80 min and that all players are similarly fatigued. Studies are required to assess the potential impact on injuries, but this structure may favour lighter players.

The flow of the game

The adoption of video technology to assist refereeing decisions at the highest levels of the game has led to prolonged delays during the match where foul-play and the validity of scores are checked to ensure fairness. Some games now last >2 hours with slow movement from set-piece to set-piece. These well-intentioned interventions may have become unintentional enablers of the physical ‘arms race’ by allowing heavier players, who fatigue faster, greater opportunity to recover and continue playing at a higher intensity with less need to conserve energy. Likewise, there are frequent delays for discussion among players before scrums and line-out, with water carriers, medical staff and others coming onto the pitch. To support a faster game, referees might stop play only for gross law infringements, limiting interventions for minor offences and playing longer advantage periods, as well as penalising delays to a line-out or scrum.

Laws of the game

We have previously stated that failing to adhere to set-piece laws may have driven changes in players’ physical characteristics.⁴ Allowing the scrum feed to be crooked has enabled larger hookers in the front row and the call for a straight put-in at the scrum, along with refereeing the ruck as set down in the laws of the game. Similarly, allowing players to lift one another in the line-out has coincided with a significant gain in the body mass of second-row forwards. If they were to have to jump for the ball themselves, this may mean that lighter players, able to project themselves higher, would be more successful, stalling increases in body mass.

The ‘physical arms race’

The development of greater forces applied by players coincides with enormous concern about player welfare in the form of injuries, recognised at the time and identified at later time points. As far as we are aware, it is not feasible to limit a player’s speed or body mass. However, one route to lower the peak momentum regularly achieved would be to enforce a team ‘weight limit’ so that the combined body mass of the 15 players on the pitch did not exceed a predetermined total. This would allow teams to field some heavy players but may create an environment where lighter players with different physical attributes and skillsets are prioritised.

Limitations

A limitation of these data relates to it being comprising three teams, and thus there are two time-points at which whole squads’ change (in 2003 and 2014) may have affected some of the results. Mitigating this, player turnover within a team was typically 10–15 players per season in squads of 45–50 personnel. We extrapolated distance covered in players who left the field after >50 min of playing (either through injury or tactical substitution), which may over-represent the results of the player groups frequently replaced after about 60 min (eg, often the

entire front row). It should also be mentioned that information that would enable us to relate the significant changes we observed to changes in actual risk of physical injury was not available. Nevertheless, circumstantially, the increases in mass and momentum with the time that we observed did coincide with increased rates of injury reported over the same period, encouraging more focused attention on the quantitative relationship between performance measures and injury risk.

GPS was not established as the gold-standard measurement platform for all teams until around 2010. Despite using the same sprint dash times over timing gates as their maximal speed measurement tools, some used 30m. In contrast, others used 40m as a distance. A limitation is the reliability of the conversion of m/s from the maximal speed obtained from a 'flying' 30m to its measurement using GPS systems.

Summary

Our new dataset, gathered over 20 seasons of top-flight rugby, has shown that professional players are now leaner, heavier, faster and cover more distance than ever before. When professional rugby players collide, the forces involved have risen. The implications of this are yet to be fully understood. Still, a growing evidence base for concerns over head injuries means serious consideration of longitudinal datasets such as this, and how to address the consequences of players' changes over time is now urgently required.

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