Physical Therapy in Sport 75 (2025) 72–79

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

The effect of neck strength and anthropometric properties on the linear and rotational accelerations experienced by academy footballers during heading: an exploratory analysis

Phil Bolland [a,c], Thomas Mullen [b], Nick Dobbin [c,*]

[a] Liverpool Football Club, Liverpool, UK
[b] Department of Sport and Exercise Sciences, Manchester Metropolitan University Institute of Sport, Manchester, UK
[c] Department of Health Professions, Faculty of Health and Education, Manchester Metropolitan University, Manchester, UK

ARTICLE INFO

Keywords:
Non-concussive force
Football heading
Instrumented mouthguard
Head impact

ABSTRACT

Objectives: To examine associations between anthropometric properties and neck strength with linear and rotational accelerations during heading.
Design: Observational cohort study.
Participants: Eleven male footballers from a UK academy.
Main outcomes: Independent variables included head and neck circumference, head mass, head-neck segment mass, and strength. Dependent variables were mouthguard-derived linear and rotational acceleration.
Results: A total of 11 male footballer recorded 259 heading events (24 ± 8 per player). Trivial associations were observed between neck length, head-neck segment mass, and side flexion strength with linear acceleration ($r = -0.04$–0.18, p = 0.001–0.638). There was trivial-to-small association between neck circumference, head mass and strength in forward flexion and extension with linear acceleration ($r = 0.05$–0.33, p = 0.001–0.602). Neck circumference, head mass, and strength in forward flexion and extension showed trivial-to-small associations ($r = 0.05$–0.33, p = 0.001–0.602). Neck length, circumference, and side flexion strength showed trivial-to-large associations with rotational acceleration (r = −0.17–0.70, p < 0.001–0.166), while head mass, head-neck segment mass, and strength in flexion and extension had trivial-to-small associations ($r = 0.01$–0.75, p < 0.001–0.955). Fixed effects explained 4.3–6.5% of the variance in linear and rotational head accelerations.
Conclusion: Neck strength and anthropometric factors showed mixed associations with head accelerations during heading, explaining a small proportion of the variance in linear and rotational accelerations.

1. Introduction

There is growing recognition of the potential impact that repeated non-concussive incidents (e.g., heading) may have on football (soccer) players' short- and long-term well-being, including the risk of developing neurodegenerative disease. (McKee et al., 2014; Mackay et al., 2019; Pearce et al., 2018). Research has attempted to substantiate these concerns using retrospective datasets from large populations of footballers who subsequently developed neurodegenerative diease at higher rates that those obsered in non-sporting populations (Mackay et al., 2019; Russell et al., 2021; Ueda et al., 2023). Such evidence, combined with media attention on several high-profile cases, has prompted national governing bodies to implement rule changes aimed at reducing the accumulation of non-concussive force over players' careers, around 90% of which result from impacts caused by heading, occuring at a rate of 0.3 to 1 per player hour (Brooks et al., 2021; Filben et al., 2022). In 2015, the United States Soccer Federation banned heading for children aged 10 years and under, and placed a restriction on those aged 11–13 years (US Youth Soccer Policy on Players and Playing Rules, 2022). In 2021, the Football Association (FA) adopted a similar approach and released guidance for heading during training.Players below the age of 11 (e.g., under 6s to under 11s) are discouraged from heading the ball, with a low-level introduction of heading practice during training culminating in 5–10 headers per week as players progress from under 12s to under 18s (The Football Association, 2021). More recently, this guidance has evolved to include a trial of a 'blanket ban' on heading

* Corresponding author. Department of Health Professions, Manchester Metropolitan University, Manchester, M15 6GX, UK.
E-mail address: N.Dobbin@mmu.ac.uk (N. Dobbin).

https://doi.org/10.1016/j.ptsp.2025.07.008
Received 7 June 2024; Received in revised form 2 June 2025; Accepted 21 July 2025
Available online 22 July 2025

during under 12s football matches for the 2022 to 2023 season (The Football Association, 2022).

Notwithstanding the positive intentions of the governing bodies in implementing rule changes to minimise the short- and long-term risks associated with repeated non-concussive impacts under a 'precautionary principle,' the extent to which this approach will influence the long-term well-being of players remains unknown. It is anticipated that robust cause-and-effect relationships will take several decades to establish, particularly when exploring the long-term effect of banning heading in football. The regulation of perceived safety within a sport can lead to several unintended consequences, as seen in other sports (e.g., "crown of the helmet rule" in American football; Hanson et al., 2017). Firstly, banning or limiting the number of headers (e.g., <5 per week) is likely to be difficult to implement in club environment, especially when heading remains a key feature of the sport. Secondly, younger players may develop reduced technical proficiency in heading, which could affect their ability to perform at (i) higher levels of competition (e.g., U23s) or (ii) in other countries where heading is both permitted and unreastricted (Peek et al., 2020a). Finally, coaches and support staff may unintentionally devote less time to developing heading technique, neck strengthening, or addressing factors that could reduce non-concussive forces during other football-specific activities (e.g., whiplash-like movements during tackles or collisions). In the absence of strong causal links demonstrating that banning heading is effective for reducing the risk of neurogenerative disease at present, an alternative method might be to reduce the risk of non-concussive forces caused by the linear and rotational acceleration during heading activity using low-cost and scalable methods suitable at all levels of the game, while also placing limits on heading frequency. These methods might include developing technical proficiency, implementing neck strengthening programmes (Blyth et al., 2025), and enhancing anthropometric or physical characteristics that reduce linear or rotational accelerations during heading.

It is anticipated that football players experience several thousand non-concussive impacts across a career, with recent work attempting to quantify these using accelerometers that measure linear and rotational acceleration (Gutierrez et al., 2014). Considerable focus has been placed on repeated heading, which has been defined in various ways across the literature (Peek et al., 2024), but generally refers to a purposeful action directing the football with the head, ideally using the thick frontal bone of the skull with neck muscles braced to reduce resultant head acceleration in a backward direction (Erkman, 2009). However, youth football players may not yet have developed the required neck strength to adequately brace the neck (Babbs, 2001) during the wide range of heading actions or delivery modes commonly observed during matches (Bradberry, Cairns, and Peek, 2024; Filben et al., 2022; Kenny et al., 2022; Langdon, Goedhart, Oosterlaan, and Königs, 2022). Further consideration is needed for key anthropometric measures such as head size, head mass, head–neck segment mass, neck circumference, and neck length, as depending on their relative ratios, they may contribute to greater momentum and segment acceleration (Babbs, 2001; Ghiri et al., 2025; Mansell et al., 2005). O'Kane (2016) reported that youth players have smaller heads, less trunk and neck strength to stabilise the head, and potentially poorer technique. Thus, they might be less efficient at transferring energy from the head to the ball, leading to greater angular accelerations compared to adults. Research exploring the link between anthropometric and strength measures with mild traumatic brain injury (mTBI) incidence or head accelerations has produced mixed results (Conney et al., 2022). One study found lower neck circumference and neck strength in those who sustained an mTBI compared to those who did not (Collins et al., 2014); however, these findings have not been replicated elsewhere (for example, Esopenko et al., 2020).

An association has also been observed between head accelerations (linear or rotational) and neck strength (Bretzin et al., 2017; Eckner et al., 2014; Fitzpatrick et al., 2021; Gutierrez et al., 2014), head–neck segment mass (Tierney et al., 2008), neck girth (Tierney et al., 2008), and head circumference (Teymouri et al., 2012) among football and contact sport athletes. However, these findings are not consistent, with two studies reporting minimal association between neck strength and head accelerations (Dezman et al., 2013; Teymouri et al., 2012). Whilst this body of work provides important, albeit mixed, insights, its external validity is limited because most studies are lab-based experiments using 10 to 20 controlled headers (i.e., with the same speed and direction), which poorly reflect the stochastic and unpredictable nature of football. More recently, Filben et al. (2021a, 2021b, 2022, 2024) and Kenny et al. (2022) have sought to understand head kinematics during training and match-play. For the most part, this work has explored factors associated with greater or lesser accelerations, with a focus on aspects such as heading technique (e.g., using the forehead results in lower accelerations), positional differences, ball delivery type, and the intention of the header by state of play. Whilst this research advances our knowledge, it is limited to young or collegiate female soccer players, who likely possess different anthropometric and strength characteristics compared to male players.

The increase in evidence exploring head acceleration in training and match environments largely reflects the development of instrumented mouthguards, which measure linear and rotational acceleration and allow for greater ecological validity. However, further work is needed, particularly in male soccer players in order to understand the accelerations in routine training practice, where the total head impacts is significantly greater than in matches (Filben et al., 2022). Furthermore, whilst research has explored the role of neck strength, this has often been collected using hand-held dynamometry and the application of the 'make condition', which is known to underestimate force output compared to fixed methods (Ashall et al., 2021). Finally, understanding the independent effects of a range of anthropometric measures is warranted. Therefore, with recent advances in technology, including fixed frame dynamometers and instrumented mouthguards, which are becoming increasingly accessible within sport, this study aimed to examine the association between anthropometric characteristics and allometrically scaled neck strength (measured using fixed dynamometry) and linear and rotational accelerations (measured using an instrumented mouthguard) during football activity.

2. Methods

2.1. Participants

Eleven football players (defenders, $n = 5$; midfielders, $n = 4$; and strikers, $n = 2$) with 8–12 years' of playing experience and 1–2 years' experience at a category one academy in the United Kingdom were recruited (age $= 18.2 \pm 0.4$ years). All participants were on a full-time programme and had medical clearance to participate in the study at the start of the eight-week observation period from the club's doctor and team physiotherapist. All participants were aged 16 years or older and provided informed consent after reading a participant information sheet. Institutional ethics approval was granted by the Faculty of Health and Education Research Ethics and Governance Committee at Manchester Metropolitan University (No. 41607).

The sample size for this study was considered from various viewpoints. Firstly, from a practical perspective, the population size was limited to a single club of approximately 22 players and a total of 11 custom-made instrumented mouthguards were supplied by the sport's governing body due to the cost of these devices. Statistically, the objective of this study was to assess the independent association of various fixed factors while accounting for the individual slope rather than estimating the between-participant variances. Also, at the first level, which refers to the number of observations per individual, this was maximised as much as possible over the eight-week period. At the second level, a minimum of five participants can be sufficient to estimate the beta coefficients of the fixed factors; therefore, 11 participants was considered adequate for the current exploratory analysis (Wiley and

Rapp, 2019).

2.2. Study design

An observational cohort study design was adopted during January, February and March 2023/24, with neck strength and anthropometric assessments completed one week before commencing the observation period. During the observation period, linear and rotational data were collected from instrumented mouthguards during 13 *typical* field-based training sessions completed over an eight-week pre-season period.

The observation period was intentionally chosen to reflect the diverse range of on-field activities that academy footballers would engage in. An overview of the activity types and durations is presented in Table 1. Across the eight-week period, players engaged in 13 field sessions as well as 3 to 4 gym-based sessions per week. During all field sessions, a size 5 football was used with an estimated pressure of 9–11 psi, circumference of 68–70 cm, and a weight between 410 and 450 g.

The STROBE guidelines (von Elm et al., 2007) and a recent systematic review (Peek et al., 2024) were considered during the reporting of methods and results in this study.

2.3. Procedures

Anthropometric assessments included measures or estimates of body mass, stature, neck length, neck circumference, head circumference and head mass. Body mass was measured using portable scales (Seca 875, Seca Hamburg, UK) to the nearest kilogram whilst stature was measured using a portable stadiometer (Seca Leicester Height Measure, Hamburg, Germany) to the nearest centimetre. Neck length was measured as the perpendicular distance between the clavicle and auditory canal as per the fixed-frame dynamometer manufacture's instructions. This value was divided by total stature then multiplied by 100. To determine neck and head circumference, participants sat upright looking straight ahead. Circumferences were measured with a metric tape; head circumference was measured just above the glabella around the head to the superior eminence of the occipital bone and neck circumference was measured just above the thyroid cartilage and perpendicular to the long axis of the neck. Head mass was estimated from head circumference using the regression equation published by Ching (2007) ($R^2 = 0.901$). As head circumference was used in the estimation of head mass, head circumference was excluded from the statistical analysis. Head-neck segment mass was estimated using the following equation for males: head-neck segment mass = 0.026 x total body mass (Plagenhoef et al., 1983).

Isometric neck strength was assessed in a supine position in four directions, namely flexion, extension, and right and left side flexion, using the Kangatech 360 (KangaTech Pty Ltd. Australia). The KangaTech is a portable fixed-frame system (weight: 52 kg) that can measure the force against fixed load cells (sample rate: 25 Hz) in a vertical (capacity: 200 kg) and horizontal (capacity: 100 kg) direction. All assessments were conducted under the same conditions and by the same club physiotherapist who had prior experienced assessing isometric neck strength. Each testing session consisted of an introductory talk outlining the procedures. Thereafter, neck strength in each direction was assessed thrice, comprising a familiarisation test (~50 % effort), followed by two recorded maximal voluntary isometric contractions. Each repetition was held for 5 s and separated by 30–60 s of passive rest (Keep et al., 2016). The KangaTech 360 is reported to be valid (Dunne et al., 2022) and reliable (ICC = 0.915 to 0.974) (Dunne et al., 2022; Ransom et al., 2020) with a typical error of approximately 0.07–0.08 kg (2.1–3.3 %) reported by the manufacturer. The peak value from the two contractions was reported in absolute (N) and allometrically scaled terms ($N/kg^{0.67}$).

To assess the resultant linear and rotational accelerations, a dental clinician took upper and lower alginate dental impressions using a dental fitting tray and putty. The instrumented mouthguard was then custom-made by Prevent Biometrics (Minnesota, USA) using the impressions. These mouthguards are equipped with triaxial gyroscopes and

Table 1
Description of the field sessions, number of heading events observed, and number players observed reflected per session.

Week	Session	Description	Duration (mins)	Total number of headers	No. Players	Median (± IQR) number of headers per player
1	1	3 v 3/4 v 4 bouts; 8 v 8; finishing drills; 10-min self-directed activity	90	16	6	2.5 ± 1.0
3	2	Recovery session 0.2 v 1 positional work, individual work; 10-min self-directed activity	60	4	3	1.0 ± 0.5
4	3	Match prep; 2 v 1s; unit splits; 10 v 8s; 10-min self-directed activity	75	8	5	1.0 ± 1.0
4	4	Individual split; 11 v 11; heading game; finishing drills; 7 v 7; high-speed running exposure.	90	84	9	9.0 ± 2.0
5	5	Individual split; 11 v 11 with defensive focus; heading bouts; 7 v 7; high-speed running	90	32	8	3.5 ± 1.5
5	6	3 v 3/4 v 4 bouts; attackers finishing focus; 8 v 8; 10-min self-directed activity	90	18	5	4.0 ± 0.0
5	7	Individual split; 11 v 11; heading game defenders; 7 v 7; high-speed running; 10-min self-directed activity	90	22	7	3.0 ± 2.0
6	8	Match prep. 2 v 1s; Unit splits; 10 v 8 s; 10-min self-directed activity	75	11	3	3.0 ± 0.5
6	9	Recovery sessions; 1	60	10	4	2.0 ± 1.0

(continued on next page)

Table 1 (*continued*)

Week	Session	Description	Duration (mins)	Total number of headers	No. Players	Median (± IQR) number of headers per player
		box drills; 10-min self-directed activity				
7	10	Individual split; 11 v 11; heading game; 7 v 7; high-speed running; 10-min self-directed activity.	90	25	6	4.0 ± 0.0
7	11	Recovery sessions; 1 box drills; 10-min self-directed activity	60	8	6	1.0 ± 0.8
7	12	Recovery session; 2 v 1 positional work, coach-directed individual work; ball mastery; recovery runs	60	2	2	1.0 ± 0.0
8	13	Friendly game with stop/start coaching	90	19	3	7.0 ± 3.0
Total				259	–	–

accelerometers, sampling at 3200 Hz with a measurement range of ±35 rad/s and ±200 *g*, respectively. The accelerometer and gyroscope captured the linear acceleration (g) and rotational acceleration (rad/s^2) of the heads estimated centre of gravity, and the location and duration of each impact. The device demonstrates reliability, with a mean relative error of 4.9% for peak rotational acceleration and 2.5% for peak linear acc (Liu et al., 2020). All data were stored then downloaded and recorded on the X2Biosystem Injury Management Software (IMS) and transferred to an Excel spreadsheet (Microsoft Corp) for further analysis with a 200 Hz low-pass 4th order Butterworth filter was applied to remove high frequency noise. All sessions were video recorded capture the accelerations that match a purposeful heading event regardless of the magnitude observed. Once confirmed, this data was matched to the participants characteristics in long-form, resulting in multiple observations per player. Any other contacts or collisions recorded by the mouthguard were excluded from the analysis.

2.4. Statistical analysis

Following inspection of the data (i.e., raw and Q-Q plots), descriptive data were generated to provide a measure of central tendency (mean) and dispersion (standard deviation, SD). To assess the association between anthropometric and strength factors (fixed effects) and accelerations (dependent variables) whilst accounting for individual player-observations (random effects over a seven-week period (repeated factor), a mixed-effect linear model was performed for linear and rotational acceleration to explore potential associations. The model was constructed under the assumptions of differing variances and a constant correlation between repeated measures. All fixed factors were grand mean centred and scaled before being 'entered' into the model. The *t*-statistic from the final model and the degree of freedom were used to estimate the effect size correlation (Rosnow, Rosenthal and Rubin, 2000) with 95 % confidence limits, and interpreted as trivial (<0.10), small (0.10–0.30), moderate (0.31–0.50), large (0.51–0.70), very large (0.71–0.90), almost perfect (0.91–0.99), and perfect (1.00) (Hopkins, 2002). Marginal and conditional R^2 values for linear mixed-effects models were calculated as outlined by Nakagawa & Schielzeth (2023). Variance explained by fixed effects (marginal R^2) was estimated by calculating the variance of the linear predictor (Var(Xβ)) from the fixed effect estimates. Conditional R^2, representing the total variance explained by both fixed and random effects, was calculated by incorporating the variance components of the random intercept and residual variance. Fixed effect estimates and variance components were extracted from the fitted models to compute these values. Model fit and stability were assessed using information criteria (Akaike's Information Criterion (AIC), the corrected Akaike's Information Criterion (AICC), and the Bayesian Information Criterion (BIC)), convergence diagnostics, and evaluation of fixed and covariance parameter estimates to ensure interpretability and robustness given the repeated measures model structure and sample size. The AIC, AICC and BIC were compared between the null (random effect only) and full (random + fixed effects) models. All statistics were performed using IBS SPSS (version 27) (IBM Corp. Armonk, New York, USA).

3. Results

A total of 11 players and 259 'player observations' were included in this study, with 24 ± 8 heading events observed per player. All participants completed the entire sessions for which they were observed. The number of players who performed headers in each session is presented in Table 1, with all players included in at least three sessions. The median number of headers per player ranged from 1 to 9 per session. We note that no participants experienced signs or symptoms associated with, or were diagnosed with, sports-related concussion. The mean and standard deviation for each of the fixed (independent) factors are presented in Table 2. The mean and SD for the linear and rotational accelerations were 11.7 ± 4.1 *g* (range = 3.0–37.7 *g*) and 932.2 ± 679.9 rad/s^2 (range = 121.6–5810.9 rad/s^2), respectively.

In the randomeffects model, between-participant variability accounted for approximately 12.8% of the total variance in linear acceleration. Fixed effects in the full model explained an additional 6.5% of variance, while the remaining approximately 80.7% is attributed to session-level (within-player) variability. The magnitude of the

Table 2
Descriptive statistics for the fixed factors.

Variable	Mean ± SD	Min, Max
Stature (cm)	178.9 ± 5.6	166.6, 186.0
Body mass (kg)	68. 5 ± 6.6	57.6, 81.4
Neck length (cm)	15.7 ± 1.2	14.0, 18.0
Neck circumference (cm)	36.6 ± 1.6	33.3, 39.0
Head circumference (cm)	54.8 ± 3.2	47.7, 58.4
Head mass (kg)	3.2 ± 0.6	1.7. 3.9
Head-neck segment mass (kg)	5.7 ± 0.5	4.7, 6.7
Forward flexion (N)	111.5 ± 21.9	83.4, 150.1
Forward flexion (N/kg)	1.6 ± 0.3	1.2, 2.2
Forward flexion (N/kg$^{0.67}$)	6.6 ± 1.2	4.8, 8.9
Extension (N)	184.8 ± 47.1	117.7, 287.4
Extension (N/kg)	2.7 ± 0.6	1.7, 3.5
Extension (N/kg$^{0.67}$)	10.9 ± 2.4	6.9, 15.1
Right side flexion (N)	148.8 ± 31.2	99.1, 193.3
Right side flexion (N/kg)	2.2 ± 0.5	1.5, 2.9
Right side flexion (N/kg$^{0.67}$)	8.8 ± 1.8	6.0, 11.4
Left side flexion (N)	150.6 ± 41.3	92.2, 241.3
Left side flexion (N/kg)	2.2 ± 0.6	1.3, 3.1
Left side flexion (N/kg$^{0.67}$)	8.9 ± 2.3	5.4, 12.7

association between fixed factors and linear acceleration ranged from trivial-to-moderate. A small association was found for neck length ($p = 0.052$) and head-neck segment mass ($p = 0.042$), such that a one standard deviation increase (1.2 cm and 0.5 kg, respectively) would, on average, reduce the linear acceleration by 0.51 *g* and 1.11 *g*. Small and trivial positive associations were observed between neck circumference ($p = 0.192$) and head mass ($p = 0.482$) with linear acceleration, with a one standard deviation change (1.6 cm and 0.6 kg, respectively) increasing linear acceleration by 1.10 *g* and 0.20 *g*. Forward flexion ($p = 0.001$) and extension ($p = 0.602$) had moderate and trivial associations with linear acceleration, respectively. A 1.2 and 2.4 $N/kg^{0.67}$ increase in forward flexion and extension, would on average, increase the linear accelerations by 0.78 to 0.19 *g*, respectively. Left side flexion had a trivial association ($p = 0.638$) with linear acceleration where a 2.3 $N/kg^{0.67}$ increase in strength was associated a decrease in linear acceleration of approximately 0.19 g. Right side flexion had a small association ($p = 0.082$) with linear acceleration where a 1.8 $N/kg^{0.67}$ increase in strength was associated a decrease in linear acceleration of approximately 0.52 *g*. (Fig. 1).

The mixed-effect model for linear acceleration demonstrated good overall fit (AIC = 1407.20, AICC = 1429.60, BIC = 1577.93), with no convergence warnings or evidence of overparameterisation. Fixed effect estimates were stable and meaningfully enhanced the model performance when compared to the random effects only model (AIC = 1442.19, AICC = 1457.24, BIC = 1584.47).

In the randomeffects model, between-player variability accounted for approximately 12.8% of the total variance in rotational acceleration. Fixed effects in the full model explained an additional 4.3% of variance, with the remaining approximately 82.9% attributed to session-level (within-player) variability. Anthropometric measures demonstrated small-to-very large association with rotational acceleration. Neck length and circumference demonstrated a large ($p < 0.001$) and small ($p = 0.166$) association with rotational acceleration such that a one SD (1.2 and 1.6 cm) increase in length or circumference resulted in a decrease of −175.4 to −124.0 rad/s^2, respectively. Head-neck segment mass and head mass revealed trivial ($p = 0.995$) and moderate ($p < 0.001$) associations with rotational acceleration where an increase of 0.5–0.6 kg increases the rotational acceleration by an average of 132.0 and 3.2 rad/s^2, respectively. Forward flexion and extension had a very large ($p < 0.001$) and large ($p < 0.001$) association (1 x SD change = 140.5 and 185.9 rad/s^2 change, respectively) with rotational acceleration, and right and left side flexion had a large ($p < 0.001$) and moderate ($p = 0.001$) association (1 x SD change = −233.7 and −166.3 rad/s^2 change, respectively) (Fig. 2).

The mixed model for rotational acceleration demonstrated good overall fit (AIC = 3958.89, AICC = 3981.29, BIC = 4129.61). No convergence warnings or evidence of overparameterisation was observed. Fixed effect estimates were stable and meaningfully enhanced the model performance compared to the random effects only model (AIC = 3974.69, AICC = 3989.73, BIC = 4116.96).

4. Discussion

This study set out to examine the association between anthropometric properties and neck strength with linear and rotational accelerations experienced during heading activity over an eight-week observational period. More specifically, this study used technology commonly adopted within the sporting world, including instrumented mouthguards to measure head acceleration and a fixed-frame dynamometer to assess neck strength. A key finding was that the fixed factors included explained only a small proportion of the variance in the model, with the remaining variance explained by both within- and between-participant factors. Results for the fixed factors indicated that greater forward flexion strength was associated with greater linear and rotational accelerations, while neck extension strength was also positively associated with rotational acceleration. Head neck segment mass and neck length were negatively associated with linear and rotational acceleration, while head mass was positively associated with rotational acceleration.

Our results indicated that neck strength in forward flexion and extension was associated with greater linear and rotational acceleration during heading tasks in field-based activity, though the association between extension and linear acceleration was trivial. This finding contrasts with existing literature, where negative correlations (Bretzin et al., 2017; Gutierrez et al., 2014; Peek et al., 2020b) or no correlation (Dezman et al., 2013; Fitzpatrick et al., 2021; Teymouri et al., 2012)

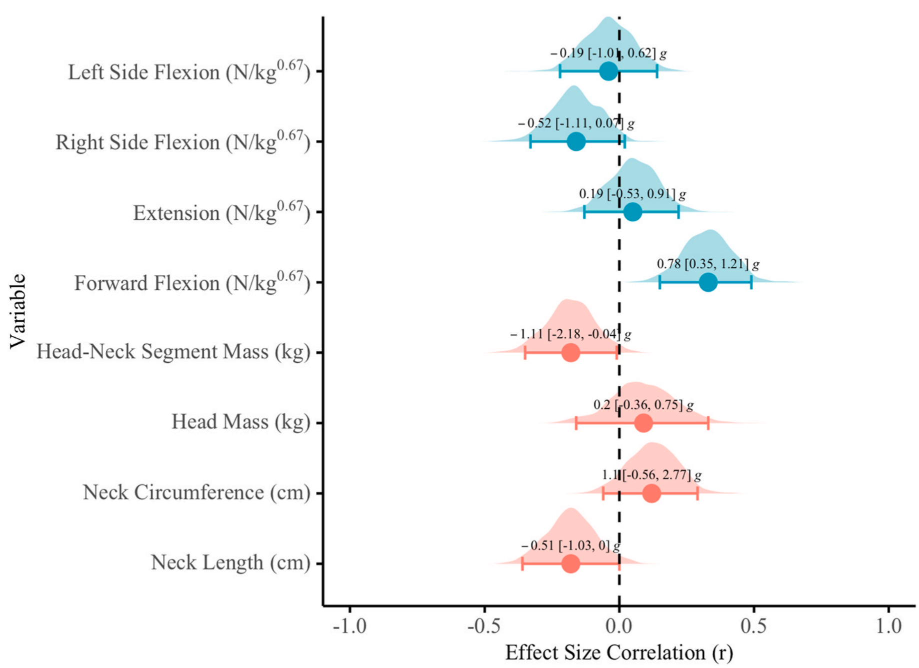

Fig. 1. Association between anthropometric and neck strength variables with linear acceleration (*g*). Note: Density plot reflect the distribution of the effect size correlation. Numbers within the density plot reflect the beta coefficient from an intercept of 11.9 g for a 1SD change in the fixed factor.

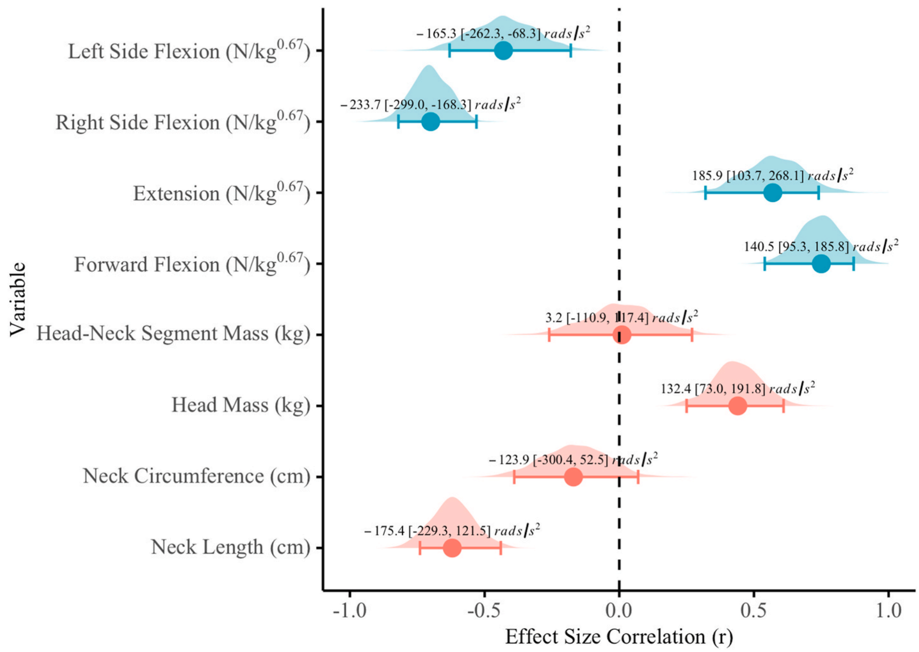

Fig. 2. Association between anthropometric and neck strength variables with rotational acceleration (rad/s^2). Note: Density plot reflect the distribution of the effect size correlation. Numbers within the distribution reflect the beta coefficient from an intercept of 823 rad/s2 for a 1SD change in the fixed factor.

have been reported. However, much of this research involved heading actions performed in controlled environments (e.g., ball launchers) rather than on-field heading during gameplay. It is plausible that greater forward flexion and extention strength facilitates a purposeful movement towards the ball and elicits greater head-to-ball contact forces, which are key features of in-game heading and may not be captured in controlled settings. For example, greater neck strength may supported increased distance during defensive headers from corner kicks, throw-ins or goal kicks, which have been reported to produce the highest linear and rotational accelerations (Filben et al., 2021a). Greater strength may also aid control, bracing and directional adjustment based on the flight path of the ball (Babbs, 2001). While previous studies have interpreted a negative association as beneficial, assuming that greater neck strength reduces brain movement and fluid displacement within the skull (Greenwald et al., 2008), it is important to distinguish between a deliberate football action (e.g., heading) and an unanticipated head impact (e.g., being struck by the ball, whiplash-like motion, or player collisions). Therefore, individuals with lower neck strength may still experience similar accelerations during a deliberate heading action, as observed in this study. Whether these different mechanisms of head impact result in distinct intracranial responses remains unknown. Nevertheless, small differences in linear and rotational acceleration may still be relevant when considering the effects of repeated non-concussive impacts. Supporting this, the mean linear accelerations recorded in our study were similar to central tendency values reported across multiple studies (e.g., Bradberry et al., 2024; Di Virgilio et al., 2016; Filben et al., 2021a, 2021b; Parr et al., 2023), though towards the lower end, reflecting shorter delivery modes (Bradberry et al., 2024), training contexts (Filben et al., 2024), and oblique headers (Huber et al., 2023). Of particular interest is the similarity to the work of Di Virgilio et al. (2016) and Parr et al. (2023), who observed negative changes in electrophysiological and cognitive function following 20 standardised headers that produced accelerations comparable to those in our study. Whether increased neck strength in forward flexion and extension alters the electrophysiological and cognitive responses reported in previous studies, either negatively due to greater accelerations or positively by reducing the perceived impact of the ball on a static head, remains to be determined. That said, limiting the number and magnitude of head impacts that result in high accelerations is likely important.

Left- and right-side flexion neck strength demonstrated unclear associations with linear acceleration and negative associations for rotational acceleration. This suggests that greater isometric neck strength was associated with reduced rotational acceleration during heading. In practice, this may suggest that greater neck strength in lateral flexion enables players to contact the ball in a more side-on or oblique position, reducing the need for full-body alignment or rapid trunk rotation to achieve forehead contact. A stabilised approach may contribute to lower linear and rotational head accelerations, as observed in studies comparing oblique to frontal headers (Huber et al., 2023). Previous studies looking at left- and right-side flexion have found a negative correlation with linear acceleration during heading the ball at two speeds (Breztin et al., 2017), and when the ball delivery was from a forward, left, and right direction (Gutierrez et al., 2014). To the authors knowledge, no direct association has been reported between neck strength and rotational acceleration, despite the negative correlations previously reported by Breztin et al. (2017) for neck girth and rotational acceleration ($r = -0.551$ to -0.669). The unclear association with linear acceleration may be due to the method of determining strength within this research (i.e., isometric muscle contractions) not adequately representing the action of heading a football involving the stretch-shortening cycle and with a degree of rotation. As such, future work is needed to assess neck strength in all directions through range using an isokinetic dynamometer. Further, the direct correlation between neck strength with rotational acceleration in a game-like scenario warrants further investigation.

Various anthropometric outcome measures have been explored including head mass, neck length and circumference, and head-neck mass (Bretzin et al., 2017; Collins et al., 2014; Kelshaw et al., 2018; Tierney et al., 2008). We observed that individuals with a larger neck circumference may experience higher linear accelerations during heading. This phenomenon appears to stem from the ability of those with greater neck circumference (as an indirect marker of musculature) to generate more force when heading. As such the observed association with forward flexion and linear acceleration may results from deliberate forceful heading actions rather than experiencing greater accelerate due to ball impact alone. Conversely, neck length demonstrated a small negative association with linear acceleration, suggesting that players with longer (albeit within a narrow range of 4.0 cm) necks may experience lower linear accelerations. Though speculative, this distinction could be attributed to the positional differences in heading technique. For example, central midfielders and strikers (mean neck length = 16.2 cm) might perform more glancing headers with larger rotational forces to progress the ball towards the oppositions goal, whereas defending players (mean neck length = 15.2 cm) might perform more powerful headers whereby they plant their feet and head the ball with greater linear acceleration to progress the ball as far as possible up the field (Erkmen, 2009). The results for head and head-neck mass are interesting. Head-neck segment mass showed a small negative association with linear acceleration and no clear effect on rotational acceleration, potentially reflecting increased moment of inertia and segmental damping. However, the contrasting positive association between head mass alone and rotational acceleration may suggest that segment-level dynamics are more complex. While a greater head mass might be expected to resist angular acceleration due to increased moment of inertia (Ghiri et al., 2025), our observed positive association may reflect the dynamic nature of heading in game-play. Players with greater head mass may generate more powerful and rotationally directed movements, potentially increasing rotational acceleration and momentum through different neck and body movements. Additionally, head mass may act as a proxy for other biomechanical or technical factors, such as heading strategy (e.g., attacking cf. defending), changes in centre of mass, coordination, or neck strength, that were not fully explored here. These findings may suggest that real-world heading dynamics required further investigation into individualised biomechanics and the importance of technique and purpose during heading actions to offer more causal relationships.

5. Limitations

There are several notable limitations in this study worthy of mention. Firstly, this was an exploratory study focusing on the independent effect of anthropometric and strength measures. Thus, much of the variance in linear and rotational acceleration has gone unexplored in this study. Evidence has emerged over the last 4–5 years that factors such as ball delivery mode (Filben et al., 2022; Kenny et al., 2022; Bradberry et al., 2024; Blyth et al., 2025; Barnes-Wood et al., 2024), intention (Filben et al., 2021a), other bodily movements (e.g., back extension; Filben et al., 2022), ball-head interaction, and technique (Filben et al., 2022; Kenny et al., 2022; Huber et al., 2023) can explain much of the within-participant variances during on-field heading. Further, age (Fiben et al., 2021b; Bradberry et al., 2024), playing experience, playing position (Fiben et al., 2022), technique (Filben et al., 2022), head mass (Ghiri et al., 2025) and strength (Bradberry et al., 2024) can explain between-participant variability. However, can cannot offer any insight into the role each of these factors play independently or collectively. Furthermore, the inclusion of isometric rather than isokinetic strength could be seen as a limitation when associated with a dynamic movement. We also limited inclusion of data to clear and obvious heading events and not head-to-head contact or head-to-ground contact during a head action. Finally, our sample included a relatively small number of players associated with a single club which may potentially limit the degree of precision and generalisation of the findings to others with different exposure to heading and varying techniques.

6. Conclusion

Overall, our study contributes to a better understanding of the factors influencing the forces experienced by academy football players during heading with consideration for purposive actions versus impacts to the head when considering the role of neck strength. Our results may contribute to future development of targeted interventions aimed at enhancing player safety allowing governing bodies, coaches, and sports medicine professionals to implement evidence-based strategies to reduce injury risk and promote the long-term well-being of football players.

CRediT authorship contribution statement

Phil Bolland: Writing – original draft, Investigation, Data curation, Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Thomas Mullen:** Writing – review & editing, Formal analysis, Writing – original draft. **Nick Dobbin:** Writing – original draft, Supervision, Formal analysis, Writing – review & editing, Visualization, Methodology, Conceptualization.

Ethics

This study was approved by the Faculty of Health and Education Research Ethics and Governance Committee at Manchester Metropolitan University (No. 41607). Written informed consent was given by all participants. In accordance with the UKRI statement with the MRC, those aged between 16 and 18 years are permitted to given informed consent if deemed Gillick competent.

Funding

No funding is associated with this research.

Declaration of competing interest

The authors report no conflict of interest. PB was employed by the club used in this study.

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