# The role of player mass and contact speed on head kinematics and neck dynamics in rugby union tackling

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**ABSTRACT**

Tackling is the most common cause of general injuries in rugby union, with player speed and mass identified as risk factors. This study aimed to use multibody modelling simulations to examine how tackler and ball carrier mass and contact speed affect inertial head kinematics and neck dynamics. Simulations were run by independently varying the ball carrier and tackler mass (from 60-110kg) and speed (from 0-10m/s). Peak resultant inertial neck dynamics (force and moment) and head kinematics (linear acceleration, angular acceleration and angular velocity) were extracted from each simulation. The greatest inertial head kinematics and neck dynamics sustained by a player was when there was the greatest mass disparity in the tackle, with the lighter player experiencing greatest inertial neck dynamics and head kinematics by up to 24% in comparison to the scenario when both players were the lightest mass (60 kg). As a player's mass increased, the magnitude of their head kinematics and neck dynamics diminished, but increased for their direct opponent, irrespective of whether they were the tackler or ball carrier. For speed, the greatest inertial head kinematics and neck dynamics sustained by the ball carrier and tackler was when they were both travelling at the highest speed. In theory, large discrepancies in mass of players, and high speeds into a tackle should be avoided.

Key Words: Injury; Biomechanics; Computational Modelling

## 1. INTRODUCTION

Tackles are the most frequent match activity in rugby union [1], and have the highest propensity to cause injury, accounting for up to 58% of all game-related injuries [2]. Tucker et al. [3] found that the tackle accounts for 76% of head injury assessments. Preventing head and neck injuries in rugby union is of particular importance, owing to their high frequency [4], and growing concerns surrounding their medium- and long-term consequences [5-7]. The force transferred through the body during legal tackles can result in large inertial neck dynamics (forces and moments) and head kinematics (linear acceleration, angular acceleration and angular velocity) [8], which are associated with neck (e.g. whiplash) and concussion injury risk, respectively [9-12].

Tacklers' shoulders can experience contact forces over 3500 N during tackle bag impact reconstructions [13,14], and average total match tackles (tackled and tackling) can range from 114 to 270 per match, depending on the competition [15]. This can lead to substantial and repeated inertial loading of the head and neck. The speed of both the tackler and ball carrier into the tackle has previously been identified as a risk factor for general injury [2,16] and head injuries [17-19], with higher speeds resulting in an increased risk. Additionally, tackle height and technique have been identified as risk factors for head injury assessments [17,20-22].

Between 1995 to 2015, Hill et al. [23] found that there was a steady increase in mean body mass of male international northern hemisphere rugby union players with the average player weighing 105 kg in 2015. Fuller et al. [24] found that lighter teams were not at greater risk of injury during the Rugby World Cup 2007, and the link between mass and injury remains unproven, though concerns have been raised over the increased body mass of a player contributing to injury risk of a direct opponent in a tackle. These concerns have included proposals to reduce the number of substitutes available to teams, which has been proposed to cause a reduction in player size, as they will be conditioned for 80 minutes of play [25].

Given these concerns, it is of interest to explore how player mass and contact speed affects head kinematics and neck dynamics. Multibody modelling simulations allows tackles to be reconstructed in a highly controlled environment [8,26,27]. Such models may provide an initial understanding of how head and neck loading during a tackle varies with player physical characteristics such as mass and speed. This may provide guidance for the development of player protection strategies. Accordingly, the goal of this study is to use multibody modelling simulations to examine the role of player mass and contact speed on tackler and ball carrier head kinematics and neck dynamics during front-on shoulder tackle events in rugby union. For a two body collision, assuming no rebound, the velocity change of Body 1 can be given by Equation 1 and 2, see Appendix A for derivation.

$$\Delta v_1 = \left[ \frac{M_2}{M_1 + M_2} \right] V_{CCS} \qquad [1]$$

$$\Delta v_2 = \frac{M_1}{M_1 + M_2} V_{CCS} \qquad [2]$$

Where $\Delta v_1$ and $\Delta v_2$ is the change in velocity of Body 1 and 2, respectively; $M_1$ and $M_2$ are the mass of Body 1 and 2, respectively; $V_{ccs}$ is the collision closing speed i.e. speed difference between the two bodies. Therefore, if $M_2 > M_1$, then $\Delta v_1 > \Delta v_2$. Given that the time to reach common velocity is the same, the average acceleration of Body 1 will be greater than Body 2. Accordingly, we hypothesise that the greatest inertial head kinematics and neck dynamics will be sustained during higher speed tackles as well as by a lighter player during a tackle with a heavier player in the more advanced multibody modelling simulations which can dissipate force through viscous damping in contacts and joints and can transfer energy between the impact point of application and the head/neck through a combination of the inertial properties of the segments and the joint configurations.

## 2. METHODS

### 2.1. Multibody Model

The MADYMO ellipsoid human body model was used as a basis for simulating player to player contact during the rugby union tackle reconstructions [8]. The model consists of 52 rigid bodies connected by kinematic joints with ellipsoids for surface representation and contact evaluation [8]. The neck and head are modelled as two separate rigid bodies. The model was originally developed for vehicle pedestrian impact modelling and validated for various blunt impact locations (pelvis, abdomen, thorax and shoulder) [28-32]. The model provides reasonable predictions for head translations, rotations, head impact time and head impact velocity in pedestrian collisions [33]. The model has been used to assess head accelerations and neck forces in automotive research [34-36]. MADYMO multibody human body models have also previously been used as a tool for investigating head kinematics during impacts in rugby and Australian rules football [8,9,26,37,38]. The MADYMO pedestrian model is considered suitable for preliminary impact analysis in rugby union [26,39], with a focus more on kinematic and dynamic trends than on absolute values of kinematic and dynamic predictions [39].

### 2.2. Tackle Reconstructions

A shoulder tackle in rugby union is when the “tackler impedes/stops the ball carrier with his/her shoulder as the first point of contact followed by use of the arm(s)” [16]. The three most common player-to-player rugby union tackle orientation configurations identified by Tucker et al. [17] were simulated (Figure 1). These consisted of multibody front-on shoulder tackles for the player-to-player configuration conditions of tackler and ball carrier upright, tackler bent-at-the-waist and ball carrier upright, and tackler and ball carrier bent-at-the-waist [17]. The tackles were selected from those previously used by Tierney et al. [26] and based on the tackle configurations that aligned to the abovementioned player-to-player tackle orientation configurations identified by Tucker et al. [17] which resulted in the largest ball carrier head kinematics [26]. Player-to-player and player-to-ground contact evaluations were applied using the built-in MADYMO contact stiffness functions. The coefficient of friction for player-to-player contact was set at 0.34 similar to Frechede et al. [37]. All simulations were run using an unlocked joint condition which results in the joints of the body being free to articulate within the physiological range of motion with minimal resistance [8,26]. The simulations were run for 35 ms to provide sufficient time for peak neck dynamic and head kinematic values to be reached [8,26] and an integration time-step of 1e-5 s was used.

**Insert Figure 1 near here**

### 2.3. Mass Analysis

Using a customised Matlab script, the mass and moments of inertia of the model were scaled based on a range of player masses (60-110 kg in increments of 10 kg). This enabled the three tackle reconstructions to be repeated for an array of tackler and ball carrier mass configurations (Figure 1), see Appendix B for simulation design matrix. The speed of the tackler and ball carrier was fixed at 5 m/s i.e. closing speed of 10 m/s [40].

### 2.4. Speed Analysis

The three tackle reconstructions were also repeated for an array of tackler and ball carrier impact speeds (tackler: 2-10 m/s in increments of 2 m/s; ball carrier: 0-10 m/s in increments of 2 m/s), see Appendix B for simulation design matrix. For speed simulations, the mass of the tackler and ball carrier were fixed at 100 kg to approximate the typical elite player mass [41].

### 2.5. Statistical Analysis

Peak resultant ball barrier and tackler inertial neck dynamics (force and moments) and head kinematics (linear acceleration, angular acceleration and angular velocity) were extracted from each simulation as these metrics are associated with neck (e.g. whiplash) and concussion injury risk, respectively [9-12]. Average values from the three player-to-player orientation reconstructions were calculated for each mass and speed scenario and heat maps created for visualisation.

### 2.6. Sensitivity Analysis

A sensitivity analysis was conducted to assess the influence of player-to-player contact friction and contact stiffness on the predicted peak head kinematics and neck dynamics using a protocol developed by Fréchède and Mcintosh (2007) [37]. For player-to-player contact friction, the simulations were run with a low level coefficient of friction of 0.2 and a high level of 0.5. For player-to-player contact stiffness, the simulations were run at a low level of -20% contact stiffness and a high level of +20% contact stiffness.

## 3. RESULTS

Differences in mass between the tackler and ball carrier influenced both the inertial head kinematics and neck dynamics experienced by both players (passive models) during tackles. Large differences in mass resulted in the lighter player experiencing the greatest inertial head kinematics and neck dynamics, irrespective of whether that lighter player was the ball carrier or the tackler (Figure 2 & 3). An increase in mass for either player caused that player's head kinematics and neck dynamics to reduce in magnitude, whereas their direct opponent experienced greater head kinematics and neck dynamics.

The greatest inertial head kinematics and neck dynamics were thus sustained by the ball carrier when they were lightest (60kg) and the tackler was heaviest (110 kg), resulting in a proportional increase of up to 24% for head kinematics and 24% for neck dynamics in comparison to the scenario when both players were 60 kg (Table 1). Similarly, the greatest inertial head kinematics and neck dynamics sustained by the tackler were found when they were light (60kg) and the ball carrier was heavy (110 kg), resulting in a proportional increase of up to 23% for head kinematics and 23% for neck dynamics in comparison to the scenario when both players were 60 kg (Table 1).

Additionally, player speed influenced both the inertial head kinematics and neck dynamics sustained by the tackler and ball carrier (Figure 4 & 5). The greatest inertial head kinematics and neck dynamics experienced by the ball carrier and tackler occur when they were both travelling at the highest speed (10 m/s). An increase in speed for either player caused the head kinematics and neck dynamics to increase for both players.

The sensitivity analysis indicates that player-to-player contact friction and contact stiffness influence the magnitude of the predicted peak head kinematics and neck dynamics, however it did not appear to affect player head kinematics or neck dynamics considerably (<10% difference) in the majority of cases (Appendix C). The sensitivity analysis does not influence the abovementioned trends identified for mass and speed on player inertial head kinematics and neck dynamics.

**Insert Figure 2 near here**

**Insert Figure 3 near here**

**Insert Figure 4 near here**

**Insert Figure 5 near here**

**Insert Table 1 near here**

## 4. DISCUSSION

This study supports our hypothesis and provides initial insights into the effect of player mass and contact speed on tackler and ball carrier head kinematics and neck dynamics during front-on shoulder tackle events. Our first finding was that the greatest inertial head kinematics and neck dynamics were sustained by a lighter player during a tackle with a heavier player, irrespective of their role as a tackler or ball carrier. Our second finding was that the greatest inertial head kinematics and neck dynamics sustained by the ball carrier and tackler was when they were both travelling at the highest speed.

While no studies we are aware of have quantified position-specific interactions, the position-specific nature of rugby union suggests that the heaviest players, typically found in the forward positions of props, locks and back rows [23], tend to be involved in more frequent tackles and collisions against similarly sized players. Backs, who tend to be lighter, may more frequently encounter tackle situations against other backs. Moreover, backs execute higher speed tackles, while player speeds during tackles may be lower among forwards whose ball carries and tackles occur more frequently in close contact and reduced space [2,42]. The net result may be that backs are involved in higher speed contacts against other backs, while forwards tend to more frequently tackle other forwards. While speculative, this suggests that the risk to lighter players may be relatively reduced because they less frequently tackle or are tackled by much heavier players, but that this may be offset by the fact that their tackles usually involve players at higher running speeds. This may account for the finding that the propensity for head injuries is greater for backline positions than forwards [3,17].

Our results also provide initial guidance for the development of player protection strategies. For example, law changes and application of existing laws may be applied to enforce the offside line rules to result in lower speed tackles [17]. However, it should be noted that rule changes can lead to unintended consequences and increased injury rates [43], thus injury monitoring is essential. Additionally, our findings provide guidance on the role of player mass on head and neck loading which could have implications for age grade rugby union, for example, where lighter players (e.g. younger athletes) are allowed to play in direct matchups against much heavier players. This reinforces the requirement for the protection of lighter players that is currently achieved through age-grading and possibly even bio-banding methods used in age groups where very large differences in mass can exist whose development may also affect strength and speed [44].

### 4.1. Limitations

This study focused on front-on shoulder tackles. However, side, oblique and behind tackles also occur in rugby union [22]. The neck is modelled as one rigid body which is a simplification, given the articulation in the cervical spine [45]. A fixed height was used for the models which doesn't reflect player height demography [23]. Some players weigh over 110 kg [23], however the model could not be scaled beyond this mass. A generic unaware muscle activation condition was simulated and the ability to 'brace for contact' and actively exert force in the tackle (e.g. through leg drive [20]), both as the tackler and the ball carrier, is not considered. This may have implications that further augment our findings, since it is possible that lighter players, or those unaccustomed to playing against faster and possibly heavier players, will be unable to exert these forces sufficient to counteract what larger players apply during tackles. Specific rugby conditioning could moderate these effects, but we cannot assess these possibilities with the model utilized here. Given the abovementioned limitations, the interpretation of the results of this study should focus more on the trends identified, rather than on the absolute values of kinematic and dynamic predictions [39]. Future work should focus on reconstructing tackles using human volunteers in a motion capture laboratory to gain more realistic values of kinematic and dynamic predictions [27]. The development of active human body models has become a promising prospect in rugby union impact analysis [45]. These models enable active muscle behaviour to be exhibited by the model during an impact scenario. However, the models require muscle activation parameters as initial conditions which are not yet fully known [45]. These could be gained from motion capture laboratory trials and/or real world impact modelling using multiple camera view video footage [46-48]. Given the above, contextualising the results in terms of direct injury risk is a challenge. Additionally, neck injury criterion are typically based on vehicle impacts and may have limited applicability to non-automotive scenarios [49]. A similar MADYMO multibody model simulation study on unhelmeted sports reported mean values for concussion of 7951 rad/s$^2$ and 103.4 g [9]. Given that a biomechanically focused model of injury includes the potential for damage to accumulate through repetitive loading [50], reducing the head and neck loading environment in rugby could have considerable benefit for long-term player welfare.

## 5. PERSPECTIVE

This study provides an initial understanding of the role of player mass and contact speed on tackler and ball carrier head kinematics and neck dynamics during rugby union tackling. The greatest inertial head kinematics and neck dynamics sustained by a player occurred when mass disparity between players involved in the tackle was at its greatest and when they were the smaller player in that tackle situation. Any increase in mass of a player reduced the inertial neck dynamics and head kinematics for that player, while increasing them to their opponent. The greatest inertial head kinematics and neck dynamics sustained by the ball carrier and tackler was when they were both travelling at the highest speed, and any increase in speed of either player increased the inertial head kinematics and neck dynamics for both players. The results provide initial guidance for the development of player protection strategies in the tackle which should, in theory, minimize large discrepancies in mass of players involved in contact, and reduce contact speed.

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**Table 1.** Proportional inertial head kinematics and neck dynamics changes for ball carrier (BC) and Tackler (T) during tackles for different player mass combinations with Light T (60 kg) vs light BC (60 kg) used as the reference (base) value.

| | **Tackler (T)** | | | | **Ball Carrier (BC)** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Light BC vs Light T** *60kg BC vs 60kg T* | **Light BC vs Heavy T** *60kg BC vs 110kg T* | **Heavy BC vs Light T** *110kg BC vs 60kg T* | **Heavy BC vs Heavy T** *110kg BC vs 110kg T* | **Light BC vs Light T** *60kg BC vs 60kg T* | **Light BC vs Heavy T** *60kg BC vs 110kg T* | **Heavy BC vs Light T** *110kg BC vs 60kg T* | **Heavy BC vs Heavy T** *110kg BC vs 110kg T* |
| Head linear acceleration | 1.00 | 0.85 | 1.23 | 1.07 | 1.00 | 1.24 | 0.85 | 1.13 |
| Head angular acceleration | 1.00 | 0.77 | 1.07 | 1.00 | 1.00 | 1.18 | 0.80 | 0.97 |
| Head angular velocity | 1.00 | 0.69 | 1.21 | 0.87 | 1.00 | 1.19 | 0.75 | 0.97 |
| Neck force | 1.00 | 0.90 | 1.23 | 1.13 | 1.00 | 1.24 | 0.90 | 1.19 |
| Neck moment | 1.00 | 0.86 | 1.21 | 1.07 | 1.00 | 1.24 | 0.86 | 1.13 |

**Figure Captions**

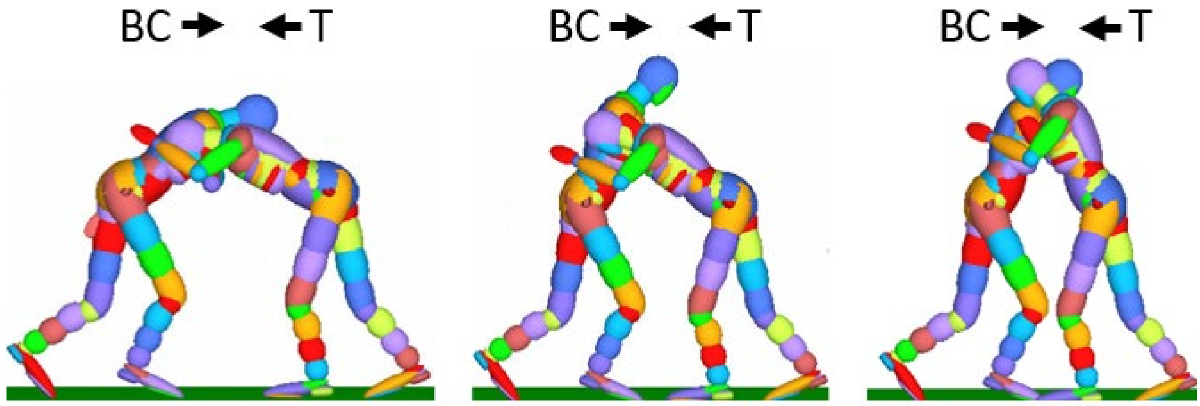
**Figure 1**. The ball carrier (BC) and tackler (T) configuration for the multibody simulations for the conditions of (a) ball carrier and tackler bent-at-waist (b) ball carrier upright and tackler bent-at-waist, and (c) ball carrier and tackler upright.

**Figure 2.** The effect of ball carrier (BC) and tackler (T) mass on inertial head kinematics for the ball carrier (left) and tackler (right).

**Figure 3.** The effect of ball carrier (BC) and tackler (T) mass on inertial neck dynamics for the ball carrier (left) and tackler (right).

**Figure 4.** The effect of ball carrier (BC) and tackler (T) speed on inertial head kinematics for the ball carrier (left) and tackler (right).

**Figure 5.** The effect of ball carrier (BC) and tackler (T) speed on inertial neck dynamics for the ball carrier (left) and tackler (right).




**(a)** **(b)** **(c)**

**Figure 1**. The ball carrier (BC) and tackler (T) configuration for the multibody simulations for the conditions of (a) ball carrier and tackler bent-at-waist (b) ball carrier upright and tackler bent-at-waist, and (c) ball carrier and tackler upright.

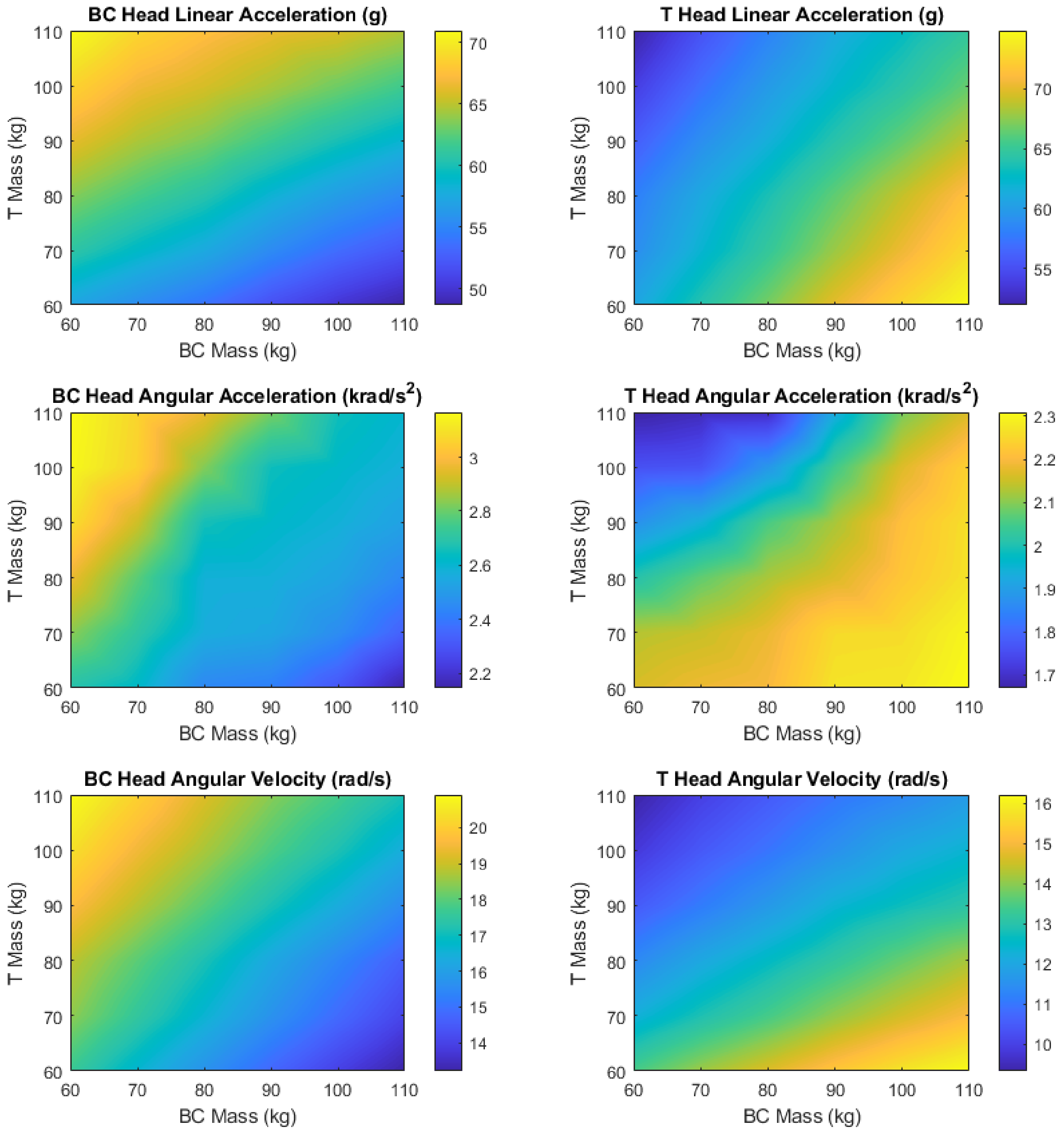



**Figure 2.** The effect of ball carrier (BC) and tackler (T) mass on inertial head kinematics for the ball carrier (left) and tackler (right).

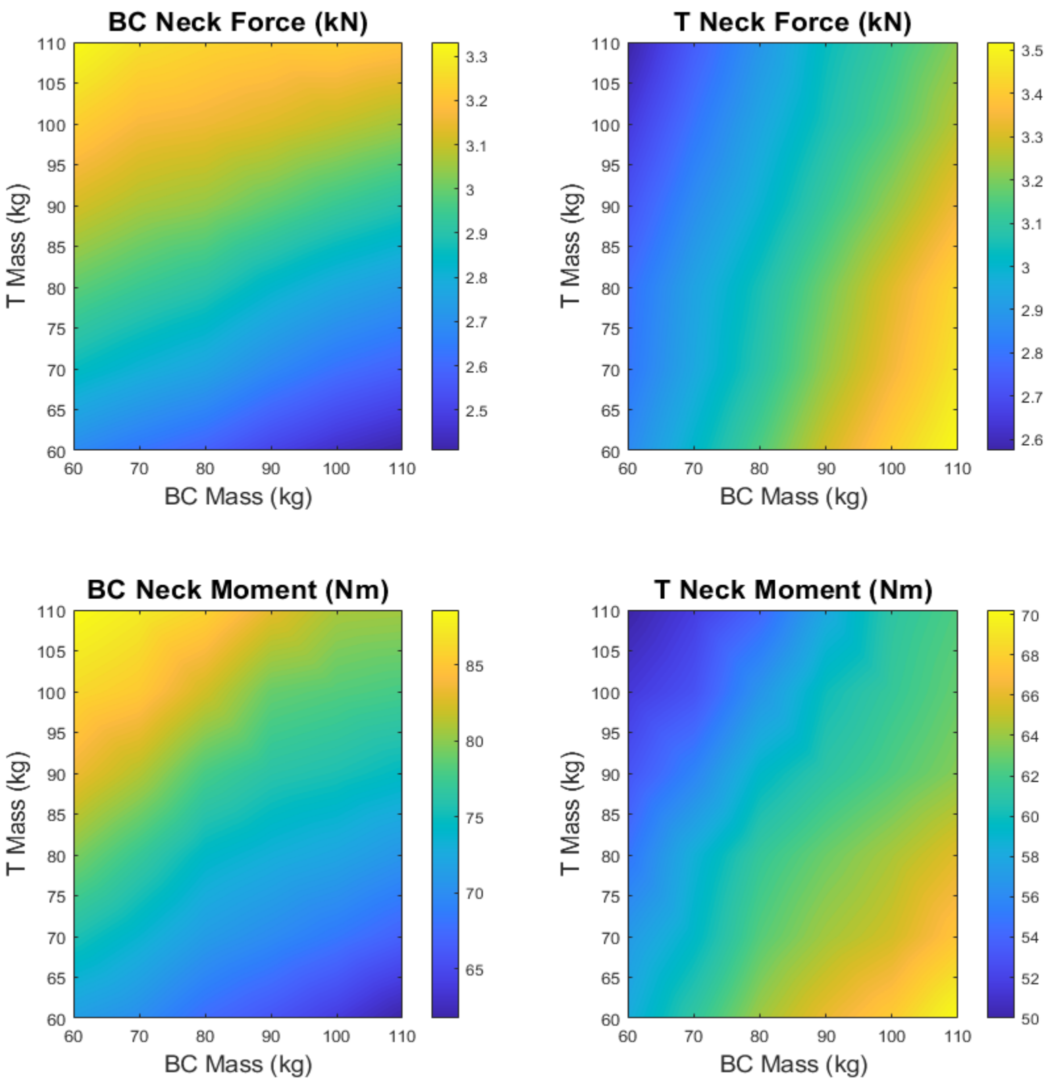



**Figure 3.** The effect of ball carrier (BC) and tackler (T) mass on inertial neck dynamics for the ball carrier (left) and tackler (right).

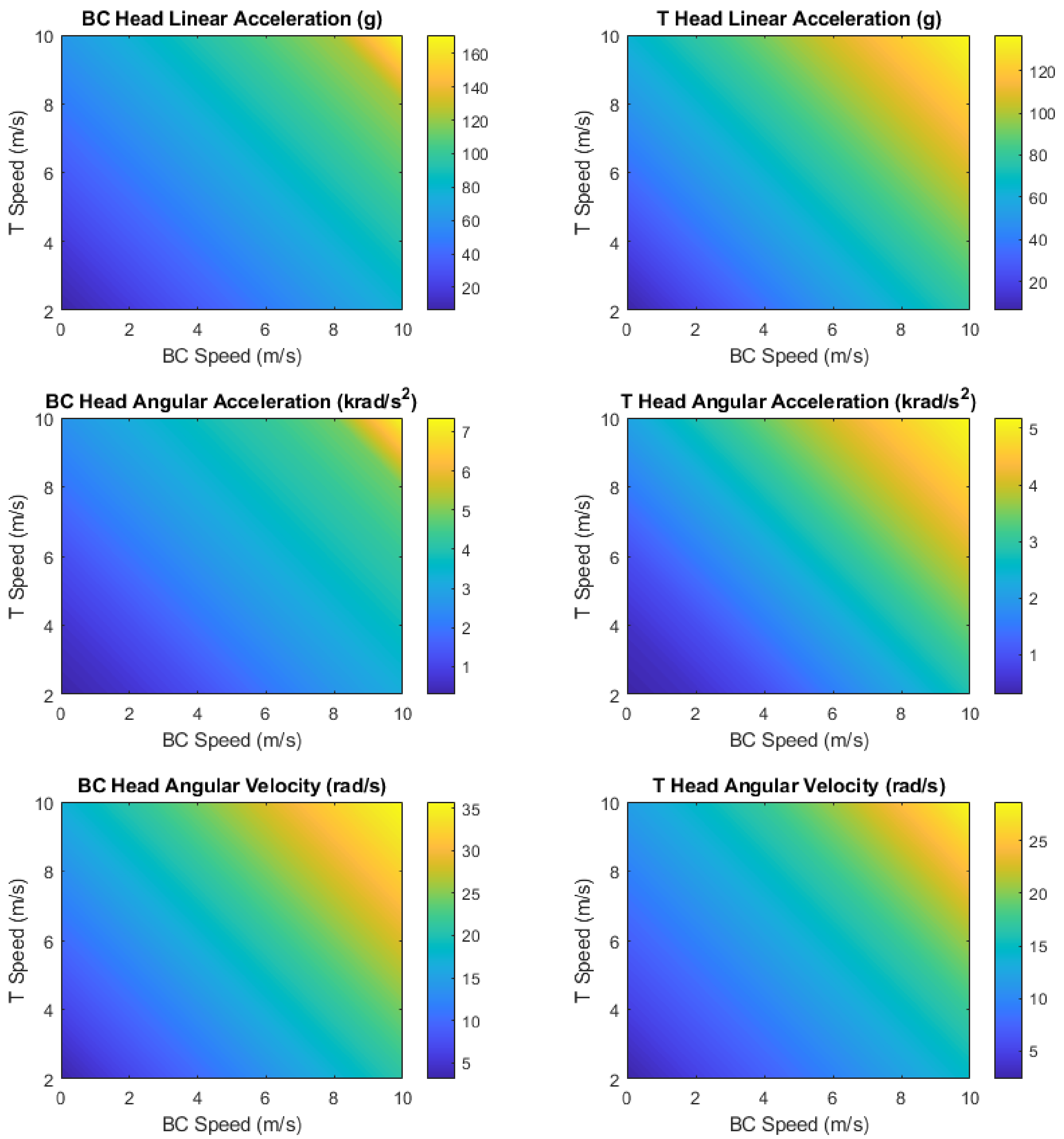



**Figure 4.** The effect of ball carrier (BC) and tackler (T) speed on inertial head kinematics for the ball carrier (left) and tackler (right).

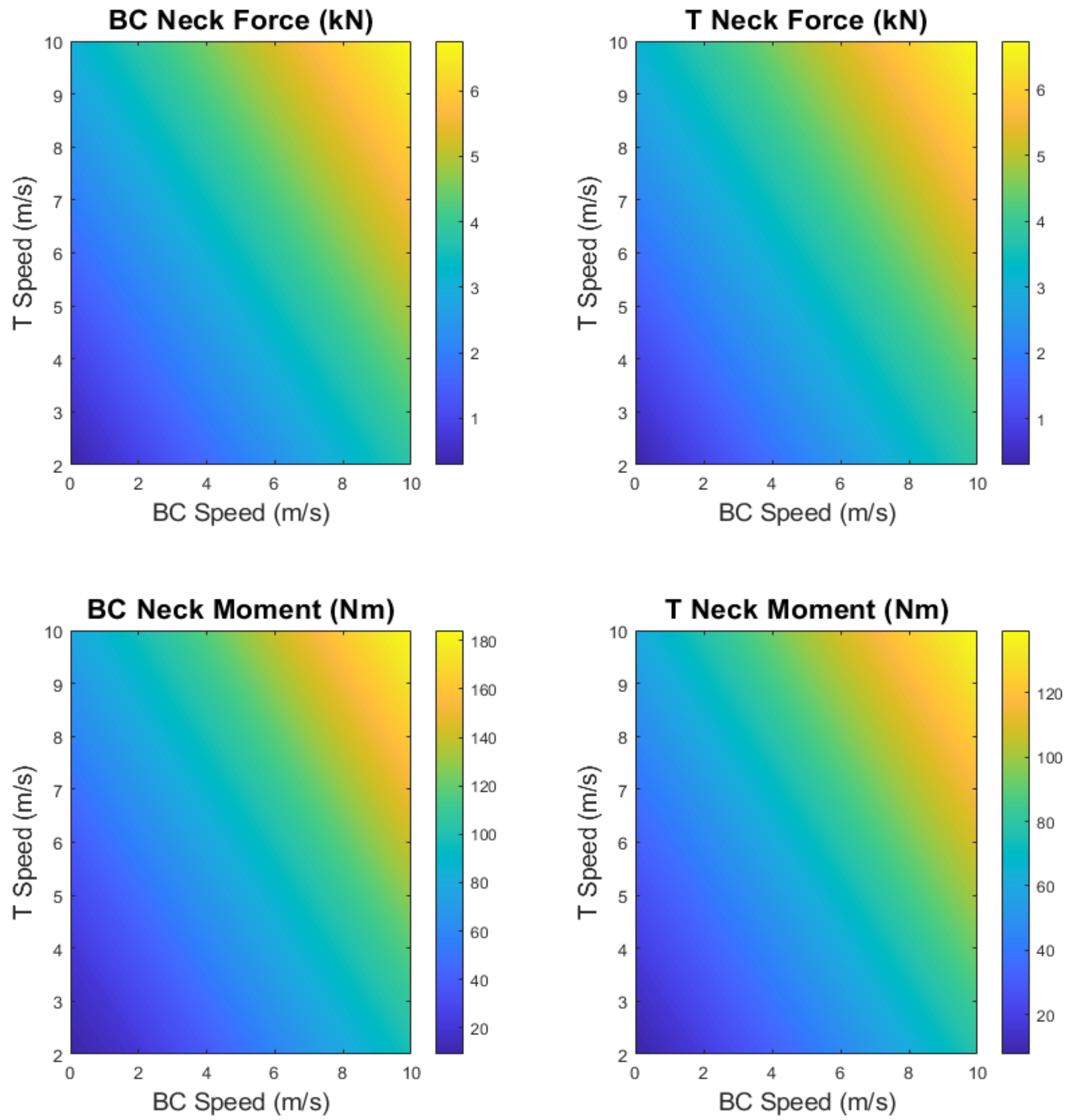



**Figure 5.** The effect of ball carrier (BC) and tackler (T) speed on inertial neck dynamics for the ball carrier (left) and tackler (right).