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INTRODUCTION

Tackling is the most common cause of injury in rugby union [1-4] and the tackle height law, which is currently set at the line of the shoulder [5], has been debated for many years now [6]. Although acute injuries, for example concussion arising from direct head impacts, are well described in rugby [7-9], there is also mounting evidence of chronic injuries to the head and neck region. Rugby players, even those without a history of concussion, have lower visuo-motor processing speeds [10] and short term visual memory [11] than participants in non-contact sports. Hume et al. [12] found that rugby players without a history of concussion have longer reaction times, psychomotor speeds as well as visual and verbal memory in comparison to age matched norms. Rugby players have also shown a compromised cervical joint position sense [13] and range of motion, and the latter correlates with time spent playing rugby [14]. Participation in a single game can reduce the cervical range of motion [15], and forwards have cervical ranges of motion similar to those of patients with whiplash [14]. Finally, the number of tackles a player engages in is related to markers of muscle damage [16, 17]. Thus, although a properly executed tackle may not result in an acute injury or require clinical intervention, the cumulative effect on the head and cervical spine of certain tackling types, especially tackles which cause high inertial loading of the head and neck, may lead to symptoms similar to an acute injury.

McIntosh et al. [18] proposed a conceptual framework for assessing injury arising from repetitive loading and an accumulation of micro-trauma, where normal loads can no longer be tolerated [18]. By measuring impact forces on a tackle bag, one study found that Tacklers' shoulders can experience contact forces over 3500 N [19] whereas another study involving staged rugby tackles between ball carrier and tackler found that the maximum force experienced was 1283 N [20]. It has also been shown that some players are involved in over 30 tackles per game [21] which can potentially lead to substantial and repeated inertial loading of the head and neck. For an amateur rugby union team over one season, King et al. [22] using instrumented mouthguards recorded 547 impacts (2.6% of total impacts) over 66g (linear acceleration) and 5653 impacts (27.3% of total impacts) over 7900 rad/s^2 (rotational acceleration) even though no diagnosed concussive head impacts were included in the dataset. This dataset was made up of direct and indirect (inertial loading) impacts. It was hypothesised that inertial loading of the head may have accounted for a proportion of these large head kinematics recorded, particularly angular acceleration [22], however no protocol was followed to examine this further. This loading environment in regular rugby union play may be responsible for some of the clinical deficits reviewed above, but the magnitude and influencing factors for head and neck loading in tackles without direct impact to the head are currently unknown.

Direct measurement of head and neck loading during tackling remains challenging with on-field measurement devices [23]. An alternative approach is through computer simulation using multibody modelling [7, 8, 24]. This approach allows for tackle reconstructions to be conducted in a highly controlled environment. This may lead to an initial understanding of the general magnitude of head and neck loading during a tackle and how this varies with tackle technique, which can assist with the development of player protection strategies and allow a greater understanding of the physiological demands during the tackle.

A recent kinematic analysis [25] distinguished legal tackles as either Upper Body Tackles (Tackler's intended primary contact being above the Ball Carrier's hip) or Lower Body Tackles (primary contact being at or below the Ball Carrier's hip) and Upper Body Tackles were the greatest cause of direct head impacts. However, this work did not include an assessment of differences in inertial loading of the head and neck between Upper Body and Lower Body Tackles.

Therefore, the goal of this exploratory study is to use multibody simulations to examine the effects of Upper Body Tackles and Lower Body Tackles on both Tackler and Ball Carrier head kinematics and neck loading in front-on shoulder tackle events where no direct contact is made with the head/neck. It is hypothesised that Upper Body Tackles cause greater Ball Carrier head kinematics and neck loading than Lower Body Tackles.

METHODS

The 50^{th} percentile MADYMO pedestrian model was used as a basis for simulating player to player contact forces during Upper Body and Lower Body Tackles. This model consists of 52 rigid bodies connected by kinematic joints and has ellipsoids for surface representation and contact evaluation. Although originally developed for vehicle pedestrian impact modelling, the model has been validated for various blunt impact locations (pelvis, abdomen, thorax and shoulder) [26-32]. There is no direct validation of this model for head acceleration and neck forces/moments. However, the model has been validated for head translations, rotations, head impact time and head impact velocity in pedestrian collisions [33]. Given that head contact on the vehicle for a typical pedestrian collision takes about 100 ms and head motion prior to vehicle contact is entirely inertial loading through the neck, these results imply broadly realistic head accelerations and neck forces/moments during that time. The model has also been used to assess head accelerations and neck forces (or injury criteria based on these parameters) in automotive research [34-36]. A similar MADYMO multibody human model has previously been used as a tool for investigating head kinematics during impacts in unhelmeted sports such as Rugby and Australian Rules Football [7, 8, 24]. Thus, although further evaluation for application to rugby is clearly needed, the MADYMO pedestrian model is suitable for preliminary impact analysis in rugby, with a focus more on trends than on absolute values of kinematic and dynamic predictions.

Initial Video Analysis

To provide estimates of player to player contact configurations, video analysis was conducted on 40 tackles (20 Upper Body and 20 Lower Body) from two randomly selected Rugby World Cup 2015 games using freely available video. Selection criteria were based on the first 10 Upper Body Tackles and 10 Lower Body Tackles from each game where the direction of the tackle was nearly perpendicular to the camera axis. For these tackles, no direct impact to the head/neck or injury occurred. The Ball Carrier and Tackler orientation were then estimated two-dimensionally by creating multibody representations of the players at the time of impact (Figure 1) to yield Ball Carrier and Tackler trunk angles with respect to the horizontal and the players' overall orientations. Results showed that, at the instant of contact, the Tacklers' trunk angles ranged from 0-90 degrees, while the Ball Carriers' trunk angles independently ranged from 40-90 degrees. These trunk angle ranges were then used for developing the multibody model player-to-player configurations for this study.

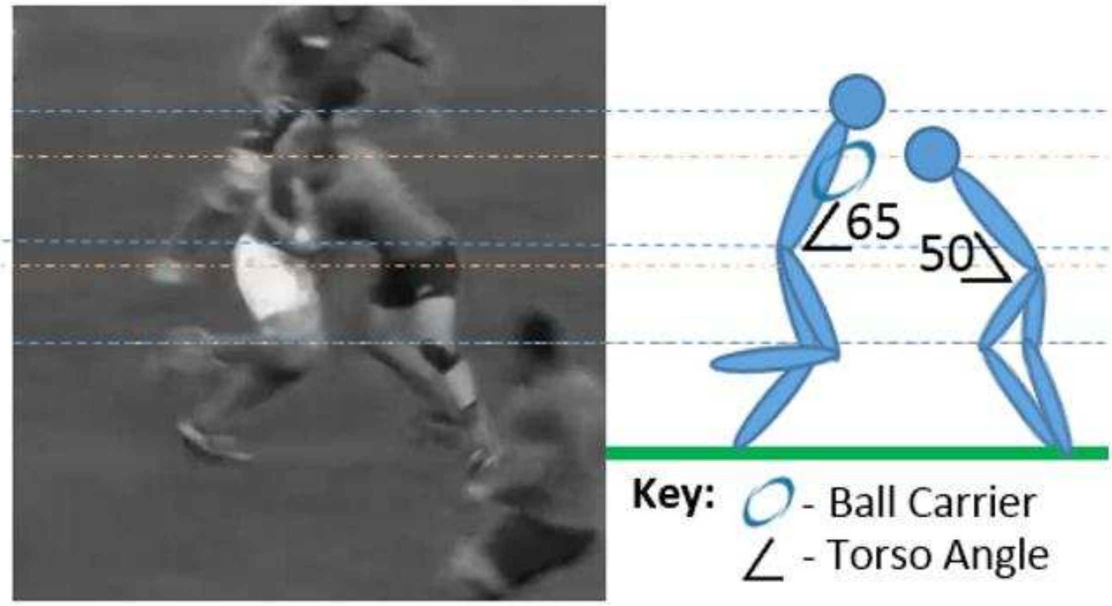

Figure 1. Two-dimensional tackle configuration with player trunk angle with respect to the horizontal for an Upper Body Tackle.

Multibody Modelling

Tackle Reconstruction

A shoulder tackle 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)" [5, 37]. Using applicable tackling and ball carrying techniques [25, 38] (e.g. head placed to the side of and not in the trajectory of the Ball Carrier), multibody front-on shoulder tackles where no direct impact to the head/neck occurred were developed using the MADYMO 50th percentile pedestrian model as a basis [32]. Using a customised Matlab script together with the MADYSCALE function, the model mass, moments of inertia and height were scaled based on average elite player height and mass (1.86 m and 101 kg, respectively) [39].. Player-to-player and player-to-ground contact evaluations using the built-in MADYMO contact stiffness functions were applied and an integration timestep of 1e-5 s was used.

For these simulations, the Ball Carrier and Tackler trunk angle were the only parameters varied to examine the effect of tackle height on the Ball Carrier's and Tackler's head kinematics and neck loading (Figure 2). For each given Ball Carrier trunk angle, simulations were run by increasing the Tackler trunk angle from zero up to the Ball Carrier's trunk angle in increments of 10 degrees. For example, for a Ball Carrier trunk angle of 60 degrees, 7 simulations were run for the Tackler's trunk angle ranging from 0-60 degrees, see Appendix A. Figure 2 shows an example of three of these configurations: the greater the Tackler trunk angle, the greater the tackle height. All tackles with a Tackler trunk angle of 10 degrees or greater are Upper Body Tackles. Although the player-to-player configurations were deliberately simplified, they were broadly representative of the actual front-on shoulder tackles identified from the video analysis. This approach resulted in 45 multibody simualtions (39 Upper Body Tackles and 6 Lower Body Tackles).

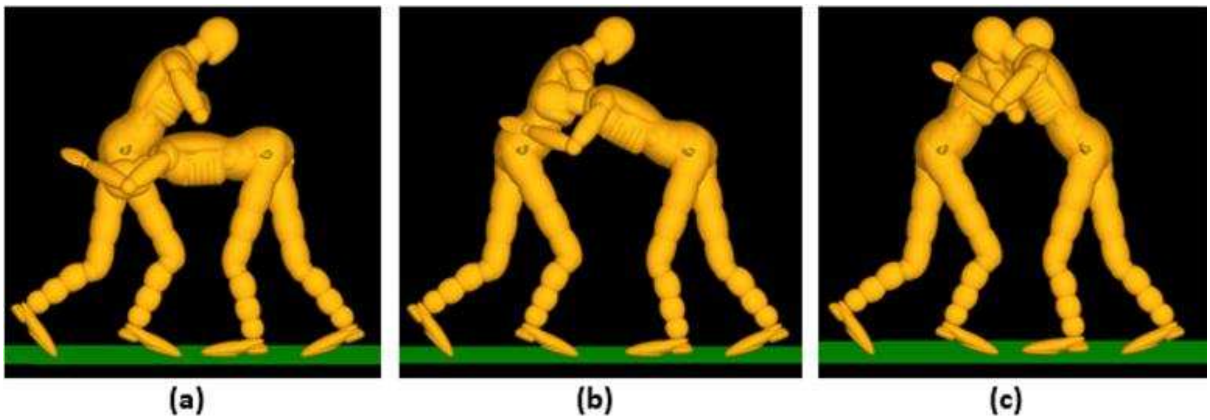

Figure 2. The player to player configuration for the Multibody simulations for the conditions of the Ball Carrier incoming trunk angle of 60 degrees and Tackler incoming trunk angle of (a) 0 degrees, (b) 30 degrees and (c) 60 degrees.

Initial velocities were based on the average elite Tackler and Ball Carrier speeds recorded 0.1s prior to impact (5.6 m/s and 4.8 m/s, respectively) [40]. The coefficient of friction for player-to-player contact was set at 0.34 [7]. Modelling muscle activation with a passive multibody model is challenging [7, 8, 24] and therefore 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. This muscle activation condition can be regarded as a low awareness state.

The simulations were run for 30 ms to include the upper bound of duration for a rugby impact in which the head experiences >10g of resultant linear acceleration [22]. All peak values were reached during this 30 ms time window. For each Upper Body Tackle (n=39) and each Lower Body Tackle (n=6) simulation, the Tackler and Ball Carrier resultant peak head linear and angular acceleration were extracted [41], as these global parameters correlate with mild traumatic brain injury [8]. Similarly, Ball Carrier and Tackler peak neck forces and moments in the saggital plane were also extracted from each simulation as these parameters are representative of possible whiplash injury mechanisms [42]. An unpaired t-test was carried out to compare differences in average peak head kinematic and neck dynamic values between Upper Body Tackles and Lower Body Tackles. Statistical significance was set at $p<0.05$. All statistics were calculated using SPSS (IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.). For each output of interest (head angular acceleration, neck force etc), the focus was placed on the ratio of the predicted average (over the different player contact configurations) of the peak Upper Body Tackle value to the corresponding average peak Lower Body Tackle value.

Sensitivity Analysis

A sensitivity analysis was used to assess the influence of the relevant model/simulation parameters identified by Fréchède and Mcintosh (2007) [7] on the ratio of predicted peak Upper Body Tackle to Lower Body Tackle head and neck kinematics and dynamics. Accordingly, the effect of player-to-player contact friction and contact stiffness as well as initial velocities on the peak head kinematic and neck loading values for both the Tackler and Ball Carrier were analysed using a protocol developed by Fréchède and Mcintosh (2007) [7]. For the low and high level friction coefficients, the simulations were run with a low level friction coefficient of 0.2 and a high level of 0.5. For contact stiffness, the simulations were run for a low level of -20% stiffness and a high level of +20% stiffness. Low and high level stiffness conditions were established by decreasing/increasing the slope of the force vs. displacement relationship for each contact in the model. For initial velocities, the simulations were run for a low level Ball Carrier and Tackler velocity (reduction of 10%) and a high level velocity (increase of 10%). Furthermore, to gain a generalised understanding of the influence of bracing through muscle activation, all simulations were run with a maximum level of muscle activation (represented by all joints locked except for the two neck joints). The locked joint condition results in the joints remaining rigid, ie. representing maximum bracing.

RESULTS

Tackle Reconstruction

Head Kinematics

For the Ball Carrier, Table 1 shows Upper Body Tackles cause higher head kinematics than Lower Body Tackles. Average Ball Carrier linear and angular acceleration values for Upper

Body Tackles were greater than for Lower Body Tackles by a factor of 2.3 ($p<0.01$) and 5.8 ($p<0.01$), respectively. The results are less straightforward for the Tackler. Upper Body Tackles caused higher head linear acceleration than Lower Body Tackles by a factor of 1.7 ($p<0.01$), however the angular acceleration values were similar ($p=0.64$).

Neck Loading

For the Ball Carrier, Table 1 shows the Upper Body Tackles cause higher neck forces and moments for the neck in comparison to Lower Body Tackles. Average Ball Carrier peak neck force and moment values for Upper Body Tackles were greater than for Lower Body Tackles by a factor of 3.1 ($p<0.01$) and 1.5 ($p<0.01$) respectively. The neck force and moment results are again less straightforward for the Tackler. Upper Body Tackles cause lower tackler neck forces ($p<0.01$) and moments ($p<0.01$) in comparison to Lower Body Tackles by a factor of 0.7 each.

Table 1: The average Ball Carrier and Tackler peak head resultant kinematic values and neck loading for Upper Body Tackles and Lower Body Tackles.

	Ball Carrier				**Tackler**			
	Upper Body Tackle (UBT) (n=39)	**Lower Body Tackle (LBT) (n=6)**	**Ratio of average UBT/LBT**	**p-value**	**Upper Body Tackle (UBT) (n=39)**	**Lower Body Tackle (LBT) (n=6)**	**Ratio of average UBT/LBT**	**p-value**
Linear Acceleration (m/s^2)	50 (±12.9)	22 (±9.6)	2.3	<0.01	61 (±14.0)	36 (±10.4)	1.7	<0.01
Angular Acceleration (rad/s^2)	2195 (±842)	379 (±78)	5.8	<0.01	1748 (±491)	1846 (±289)	1.0	0.64
Neck Force (N)	1107 (±339)	353 (±110)	3.1	<0.01	822 (±316)	1208 (±79)	0.7	<0.01
Neck Moment (Nm)	192 (±80)	132 (±26)	1.5	<0.01	192 (±47)	278 (±25)	0.7	<0.01

Sensitivity Analysis

The sensitivity analysis results showed very little influence on the predicted ratio of Upper Body Tackles to Lower Body Tackles for the Ball Carrier for the head kinematic and neck dynamic results, see Table 2. However, Table 3 shows that high muscle activation affected the principal findings for the Tackler for both angular acceleration and neck force.

Table 2: The effect of high and low level parameters in the sensitivity analysis on the ratio of average Upper Body Tackles (UBT) to Lower Body Tackles (LBT) head kinematics and neck loading for the Ball Carrier.

Ball Carrier	**Ratio of average UBT/LBT**							
	Baseline	**Muscle Activation**	**Friction Coefficient**		**Contact Stiffness**		**Initial Velocity**	
		High	**High**	**Low**	**High**	**Low**	**High**	**Low**
Linear Acceleration (m/s^2)	2.3	3.0	1.9	2.7	2.1	2.3	2.1	2.4
Angular Acceleration (rad/s^2)	5.8	3.6	5.5	5.0	5.8	5.7	5.9	5.6
Neck Force (N)	3.1	3.2	3.2	3.0	3.1	3.1	3.2	3.1
Neck Moment (Nm)	1.5	2.0	1.3	1.6	1.4	1.5	1.5	1.4

Table 3: The effect of high and low level parameters in the sensitivity analysis on the ratio of average Upper Body Tackles (UBT) to Lower Body Tackles (LBT) head kinematics and neck loading for the Tackler.

Tackler	**Ratio of average UBT/LBT**							
	Baseline	**Muscle Activation**	**Friction Coefficient**		**Contact Stiffness**		**Initial Velocity**	
		High	**High**	**Low**	**High**	**Low**	**High**	**Low**
Linear Acceleration (m/s^2)	1.7	1.9	1.5	1.8	1.7	1.7	1.7	1.7
Angular Acceleration (rad/s^2)	1.0	1.7	1.0	0.9	0.9	0.9	0.9	1.0
Neck Force (N)	0.7	1.9	0.8	0.6	0.7	0.7	0.7	0.7
Neck Moment (Nm)	0.7	0.9	0.7	0.6	0.7	0.7	0.7	0.7

DISCUSSION

General

The results of this exploratory study support the hypothesis that Upper Body Tackles cause greater head linear acceleration and angular acceleration as well as neck forces and moments for the Ball Carrier in Rugby Union even without a direct head or neck impact (Table 1). These results are not sensitive to changes in various modelling parameters tested and are within the range of reported head kinematic values gained from general rugby play [22]. Nonetheless, these findings must be considered preliminary as further model evaluation for rugby impact analysis is required.

The results of this study present initial evidence that head kinematics and neck dynamics resulting from Upper Body Tackles are higher than from Lower Body Tackles. Although it is therefore reasonable to assume that chronic injury risk is greater for repeatedly engaging in Upper Body Tackles than for Lower Body Tackles, further conclusions regarding injury risk assessment associated with Upper Body Tackles necessitate a correlation with injury data and this should be a focus of future work.

The laws of mechanics dictate that the energy transmitted during an impact is attenuated along a damped/deformable linkage system through viscous dissipation [43], thus the dynamics of the head and neck that result directly from an impact to the body will be inversely related to the distal distance of the impact with regard to these segments. Also, in a front-on shoulder tackle, the majority of Ball Carrier rotation occurs in the sagittal plane. The overall Ball Carrier angular momentum about the point of contact is conserved in the tackle resulting in greater head rotations and neck flexion/whiplash style head motions for Upper Body Tackles compared to Lower Body Tackles, as the impact on the Ball Carrier is more eccentric in Upper Body Tackles.

For the tackler, Upper Body Tackles caused higher head linear acceleration and neck forces in the simulations than Lower Body Tackles, however angular acceleration remained similar. Neck forces and moments were lower for the tackler during Upper Body Tackles. A Lower Body Tackle caused neck extension for the tackler whereas Upper Body Tackles caused neck flexion. Since the physiological range of motion for the neck in extension is less than for flexion, higher tackler neck forces and moments were caused as a result of Lower Body Tackles.

Tierney et al. [25] found that Upper Body Tackles were the main cause of direct head impacts, and hence concussion, in rugby union. The current study implies that Upper Body Tackles also cause greater loading of the brain and neck than Lower Body Tackles, even when executed properly and no direct head contact occurs. Again, significant further efforts are needed to support this using methods such as wearable head sensors [22] and reflective marker based motion analysis which should advance our understanding of the effects of tackle height on inertial loading of the head/neck. Such information can help to develop player protection strategies and reassess the maximum allowable tackle height which is currently set at the line of the shoulders [5]. The current findings support the Tackler aiming for initial contact close to the Ball Carrier's centre of gravity [44] instead of the upper body as Lower Body Tackles appear to reduce the inertial loading of the head/neck for the Ball Carrier.

Sensitivity Analysis

The sensitivity analysis showed little influence on the ratio of Upper Body Tackle to Lower Body Tackle kinematic and dynamic predictions for the Ball Carrier. Therefore, it is unlikely that the effective friction, stiffness or initial contact speeds influence the principal finding that head and neck kinematics and dynamics in Upper Body Tackles are greater than in Lower Body Tackles. The sensitivity analysis results for the Tackler are less straightforward as the principal findings for angular acceleration and neck force were affected by the high muscle activation condition in the sensitivity analysis.

Limitations

The main limitation of this study is that a generic unaware muscle activation condition was simulated. Estimates of maximum isometric joint torques of the human body can be measured and are available in the literature for most joints, for example the neck [45].

However, rugby player specific data would be beneficial and should be a focus of future work. By engaging in a tackle, the tackler should have a high level of awareness and given that the findings relating to the tackler were affected by the muscle activation condition, it is clear that developing a realistic muscle activation condition should be a focus of future work. It is recommended to generate rugby specific validation data using whole body kinematic data of rugby players during tackles, gained from either real game footage [46-48] or laboratory reconstructions.

The number of Lower Body Tackles configurations assessed is small (n=6) due to the inherent geometric constraints of this tackle configuration, see Appendix A, but the full range of Ball Carrier incoming trunk angle configurations were simulated. This study focused on multibody models of front-on shoulder tackles (i.e. Tackler impedes/stops the Ball Carrier with his/her shoulder as the first point of contact followed by use of the arm(s) [5, 37].”). However, reconstructing the “use of the arms” could not be simulated realistically in a passive model as this is a post-contact tackle characteristic [49, 50]. This means the simulations may be more representative of a collision tackle which is illegal [5]. Future work should examine the difference between collision and shoulder tackles on Ball Carrier and Tackler inertial head loading and examine how the use of the arms may reduce inertial head loading. Other post-contact tackle characteristics such as “leg drive on contact” [49, 50] could not be executed in the simulations. Arm tackles also account for about half the tackles in Rugby Union [5] and side, oblique and behind tackles also occur [51]. The simulations of the Ball Carrier did not include evasive manoeuvres or fending into contact, though these might reduce head kinematics and neck loading in the tackle. These aspects should also be the focus of future work.

CONCLUSIONS

This exploratory simulation study shows that tackle height strongly affects the head kinematics and neck loading experienced by the Ball Carrier in front-on shoulder tackles in Rugby Union, even without direct contact to the head/neck. In particular, much higher Ball Carrier head kinematic and neck loading values were predicted for Upper Body Tackles compared to Lower Body Tackles and this principal finding was unaffected by the sensitivity analysis. Tackler results were less straightforward and trends were influenced by the sensitivity analysis for muscle activation. Further investigation is required to assess if tackle height and inertial head and neck loading could be a potential catalyst for chronic head and neck injury in Rugby Union play.

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DECLARATION OF INTEREST STATEMENT

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Appendix A: Design matrix of the 45 simulations based on Ball Carrier (BC) and Tackler trunk angle with corresponding Upper Body Tackle (UBT) or Lower Body Tackle (LBT) definition.

Tackler Angle / BC Angle	0	10	20	30	40	50	60	70	80	90
40	LBT	UBT	UBT	UBT	UBT	-	-	-	-	-
50	LBT	UBT	UBT	UBT	UBT	UBT	-	-	-	-
60	LBT	UBT	UBT	UBT	UBT	UBT	UBT	-	-	-
70	LBT	UBT	UBT	UBT	UBT	UBT	UBT	UBT	-	-
80	LBT	UBT	UBT	UBT	UBT	UBT	UBT	UBT	UBT	-
90	LBT	UBT	UBT	UBT	UBT	UBT	UBT	UBT	UBT	UBT