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Abstract

Player-to-player contact inherent in many unhelmeted sports means that head impacts are a frequent occurrence. Model-Based Image-Matching (MBIM) provides a technique for the assessment of three-dimensional linear and rotational motion patterns from multiple camera views of a head impact event, but the accuracy is unknown for this application. The goal of this study is to assess the accuracy of the MBIM method relative to reflective marker-based motion analysis data for estimating six degree of freedom head displacements and velocities in a staged pedestrian impact scenario at 40km/h. Results showed RMS error was under 20 mm for all linear head displacements and 0.01-0.04 rad for head rotations. For velocities, the MBIM method yielded RMS errors between 0.42-1.29 m/s for head linear velocities and 3.53-5.38 rad/s for angular velocities. This method is thus beneficial as a tool to directly measure six degree of freedom head positional data from video of sporting head impacts, but velocity data is less reliable. MBIM data, combined in future with velocity/acceleration data from wearable sensors could be used to provide input conditions and evaluate the outputs of multibody and finite element head models for brain injury assessment of sporting head impacts.

Key Words: Concussion; Rugby; Image Processing

Introduction

Impacts are integral to many unhelmeted sports such as rugby union, rugby league and Australian rules football, and can sometimes result in concussion, which is induced by traumatic biomechanical forces (McCrory et al., 2013). While reliable reconstruction of six degree of freedom head movement patterns during sporting impacts can be challenging, a greater understanding of the mechanisms of concussion and the kinematics of concussive and non-concussive head impacts would be beneficial to guide prevention strategies (Bahr & Krosshaug, 2005).

Analysis of unhelmeted sport head impacts to gain a better understanding of the head and brain's responses often involves multibody or finite element head model simulations (Fréchède & McIntosh, 2007; Frechede & McIntosh, 2009; McIntosh et al., 2014; Patton, McIntosh, & Kleiven, 2015; Patton, McIntosh, Kleiven, & Fréchède, 2012). For example, Patton et al. (2015) used a finite element head model to estimate the regional distribution of tissue deformations in the brain by reconstructing unhelmeted concussive and non-concussive head impacts. The results showed that temporal impacts which resulted in angular kinematics, particularly in the coronal plane, were significantly associated with concussion.

These multibody and finite element head models have numerous input parameters (geometry, mechanical/structural properties, contact characteristics and initial conditions) and kinematic outputs are generally validated based on staged impact tests using cadavers (Elliott, Lyons, Kerrigan, Wood, & Simms, 2012; Hardy et al., 2001; Mao et al., 2013;

Willinger, Kang, & Diaw, 1999). Assumptions regarding these input parameters (especially the initial conditions) strongly influence the results of impact simulations (Allison, Matltese, & Arbogast, 2013; Forero Rueda, Cui, & Gilchrist, 2011; Parent, Kerrigan, & Crandall, 2011; Takhounts, Craig, Moorhouse, McFadden, & Hasija, 2013). Therefore, a method to directly and reliably measure six degree of freedom head kinematics from video data in sporting head impacts would have two direct benefits: the data can be used to reduce uncertainty in estimating the initial conditions in head impact simulations and the post impact kinematic data can serve as a validation measure for the simulation predictions. This implicitly accounts for muscle activation and stiffness during an unhelmeted sports impact. One study used video analysis to evaluate wearable head impact sensors, such as the instrumented skin patch and mouthguard. However, although these sensors can measure full 6 degree of freedom rigid body motion, the video analysis technique used in this study was limited to measuring 3 degree of freedom (sagittal plane) motion (Wu et al., 2016).

The retrospective analysis of injuries resulting from sporting events typically involves standard video coverage. This video is not primarily intended for kinematic analysis, and so lacks the calibration information typically used for three-dimensional motion analysis systems such as Vicon (Vicon, UK). Model-Based Image-Matching (MBIM) is an approach that can be used to measure six degree of freedom motion from un-calibrated video data (Krosshaug & Bahr, 2005) whereas previous methods have been limited to extracting only linear head kinematics directly from video evidence (Newman et al., 1999; McIntosh, McCrory, & Comerford, 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003; Viano, Casson, & Pellman, 2007). Even though Model-Based Image-Matching has been applied to a head injury case in skiing (Yamazaki et al., 2015), it has currently only been validated for the hip, ankle and knee joints (Krosshaug & Bahr, 2005; Mok et al., 2011). It is hypothesised in this study that MBIM has high potential for reconstructing 6 degree of freedom (DOF) head displacement time-histories in sport impacts.

Unfortunately, there is no direct dataset against which MBIM based predictions of head kinematics in sport impacts can be assessed. However, the relative velocity of a vehicle striking a pedestrian cadaver in a staged impact test at 40km/h (11 m/s) is similar to the average closing speed (10.4 m/s) in elite level rugby union tackling (Hendricks, Karpul, Nicolls, & Lambert, 2012). Therefore, staged pedestrian cadaver impact tests can serve as a useful alternative means for MBIM assessment. Also, Table 1 shows that the average duration and change in head angular velocity of concussive head impacts from rugby are broadly similar to those observed during head contact with the windscreen in a staged cadaver impact study at 40 km/h (11m/s). Although the head-windscreen linear velocity changes are certainly higher than the average value reported for rugby head impacts, the general head impact mechanism and point of contact (temporal region) of a head-windscreen contact are similar to a direct head impact in unhelmeted sports such as rugby (McIntosh et al., 2014; Tierney, Lawler, Denvir, McQuilkin, & Simms, 2016; McIntosh, McCrory, & Comerford, 2000), which results in significant head motion.

Accordingly, the goal of this study is to assess the accuracy and repeatability of the MBIM method for estimating 6 degree of freedom head displacements and velocities in a vehicle-cadaver impact case for which reflective marker-based motion analysis based head kinematic time-histories are available as an independent measure. If the MBIM approach is successful for this case, it has the potential to aid in our understanding of the motion patterns of the head in sporting collisions and could be used as a tool to further evaluate multibody or finite element head model simulations and wearable head impact sensors.

Head Impact	Duration (ms)	Change in Linear Velocity (m/s)	Change in Angular Velocity (rad/s)
40 km/h side struck pedestrian (windscreen contact)	14	13	40
Rugby Union	12 (King, Hume, Brughelli, & Gissane, 2014)	4 ± 2 m/s (McIntosh, McCrory, & Comerford, 2000)	33 (Patton, McIntosh, Kleiven, & Fréchède, 2012)

Table 1: A comparison of head kinematics in a 40km/h vehicle-cadaver impact during windscreen contact with average head kinematics in American Football and Rugby Union concussive head impacts.

Methods

Vehicle-cadaver test

The vehicle-cadaver test protocols were approved by the University of Virginia Institutional Biosafety Committee. The vehicle-cadaver test methodology used in this study has been previously described in detail by (Kerrigan et al., 2005), (Forman, Joodaki, Forghani, Riley, Bollapragada, Lessley, Overby, Heltzel, & Crandall, 2015) and (Forman, Joodaki, Forghani, Riley, Bollapragada, Lessley, Overby, Heltzel, Yarboro, et al., 2015). Briefly, the test was conducted with a deceleration-type sled (VIA systems model 713, Michigan, USA) at the University of Virginia. The striking vehicle buck was mounted on the sled and propelled into a stationary adult male cadaver in mid-gait stance (Figure 1) at 40km/h (11 m/s). This is similar to the average relative impact velocity (10.4 m/s) in elite level rugby union tackling (Hendricks, Karpul, Nicolls, & Lambert, 2012). Although the impact appears planar in Figure 1, the head exhibits substantial six degree of freedom motion (as will be seen in Figures 6 & 7).

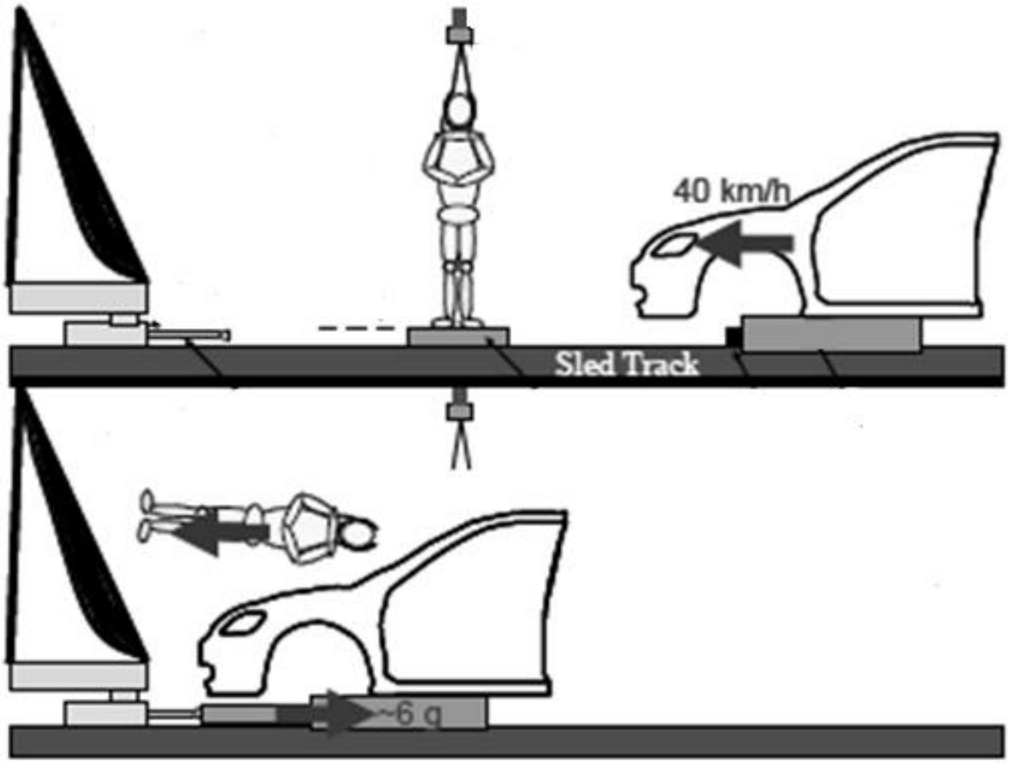

Figure 1: Schematic of the Vehicle-cadaver impact Reflective Marker-Based *Tracking*

The 3D motion data of the cadaver head in the pedestrian impact test were captured with a Vicon MX (Oxford, UK) optoelectronic motion capture system. Errors of less than 2% for both position and orientation tracking have been reported for the Vicon system (Richards, 1999). Within a calibrated volume, the reflective marker-based system uses multiple cameras to record the motion of spherical retro-reflective markers attached to the subject. The reflective marker-based system combines this information from all the cameras and thus records the 3D motion of each individual marker (Vicon, 2013).

In this test, 25 Vicon cameras were used to record the cadaver motion at 1000 fps, which is a typical sample rate of wearable head sensors (Wu et al., 2016). The arrangement of the cameras around the capture volume encompassed the entire area of interaction between the cadaver and the buck. In order to capture head kinematics, an array of seven Vicon markers was attached around the periphery of the head (Figure 2).

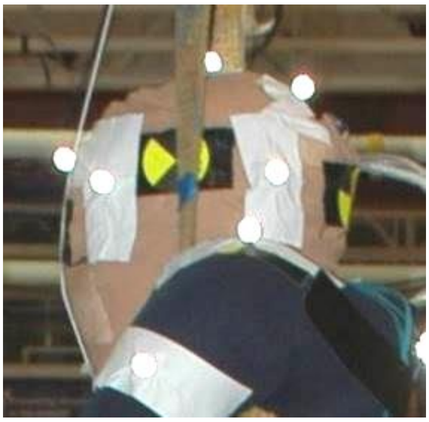

Figure 2: The Vicon marker array affixed to the external surface of the cadaver head.

Data processing was performed using Matlab. The head marker information was transformed to calculate the linear position of the head CG (midway point between the left and right zygomatic processes) and the rotation matrix for the head at each time frame. A series of successive rotations, of order yaw (ψ), pitch (θ) and roll (ϕ) (local Z, Y and X axes), were defined to record head orientation. The Matlab gradient function was used to compute the time derivatives of the yaw, pitch and roll angles and Equation 1 (O'Reilly, 2008) was used to infer the components of the head angular velocity from these:

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \begin{bmatrix} 1 & 0 & -sin\theta \\ 0 & cos\phi & cos\theta cos\phi \\ 0 & -sin\phi & cos\theta cos\phi \end{bmatrix} \begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} \quad [1]$$

where $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$ represent the time derivatives of the roll, pitch and yaw angles respectively and ω_x, ω_y and ω_z represent the angular velocity vector in the local head X, Y and Z axes (Figure 3) respectively. A low pass Butterworth filter (Cut-off frequency = 110Hz (Camarillo, Shull, Mattson, Shultz, & Garza, 2013; Hernandez et al., 2015) was applied to the angular velocity data. The cadaver was also fitted with angular rate sensors (model ARS-18K for X and Y axes and ARS-8K for Z axis, Diversified Technical System, DTS, Seal Beach, California, US) were attached to the head by means of a small aluminium plate-mount affixed to the back of the head. The resultant head angular velocities from the reflective marker-based system and angular rate sensor data were consistent with each other (less than 2% difference).

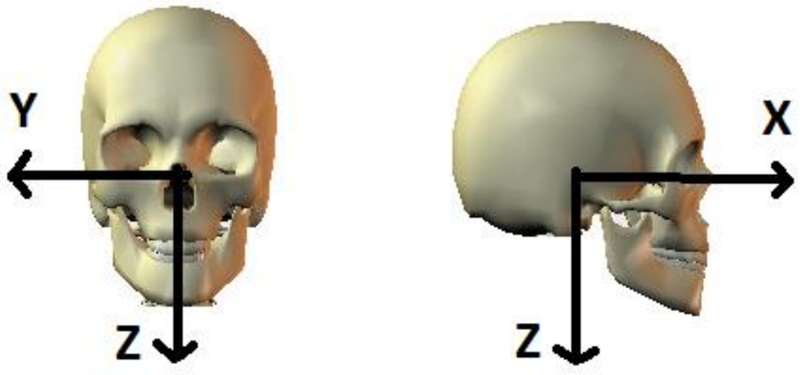

Figure 3: The local axes of the head

Model-Based Image-Matching (MBIM)

Model-Based Image-Matching has been described in detail by (Krosshaug & Bahr, 2005). Briefly, this approach uses a multibody skeleton model to estimate human body joint angle time-histories from multiple camera views of human movement. For each video frame, the skeleton model joint angles are adjusted manually to match the segment position and orientation of the model with respect to the target athlete in the multiple video views.

In this case, the matching was conducted on synchronised video of three camera views of the vehicle-cadaver impact. The resolution for each video was 800x600 pixels. The head represented approximately 24x28 pixels in Camera 1, 45x44 pixels in Camera 2 and 67x55 pixels in Camera 3. This could be considered analogous to a three camera view sport head impact for which one zoomed-in and two zoomed-out camera views are available. Three researchers (R1, R2 and R3) performed the MBIM technique to assess inter and intra-rater reliability (Researcher R1 performed the MBIM technique three times). The camera locations are shown in Figure 4, however they were treated as unknowns during the MBIM process, since camera location will not generally be known during sport impact reconstruction. The matching was performed using 3-D animation software Poser 4 and Poser Pro Pack (Curious Labs Inc, Santa Cruz, California, US). The surroundings were built in a virtual environment based on the dimensions of the laboratory. The video was imported into the background of the Poser workspace and the surroundings were then matched to the background video footage for every camera view. This was achieved by manually adjusting the camera positioning tool which contains three translational and three rotational degrees of freedom, as well as variable focal length. (Although not necessary here, this tool also facilitates application of the method to sporting cases where a camera position, orientation and zoom are changing). A skeleton model from Zygote Media Group Inc (Provo, Utah, US) was then used for skeleton matching. For this study, only the skeleton's skull was manipulated to fit the cadaver's head for each video frame (Figure 5).

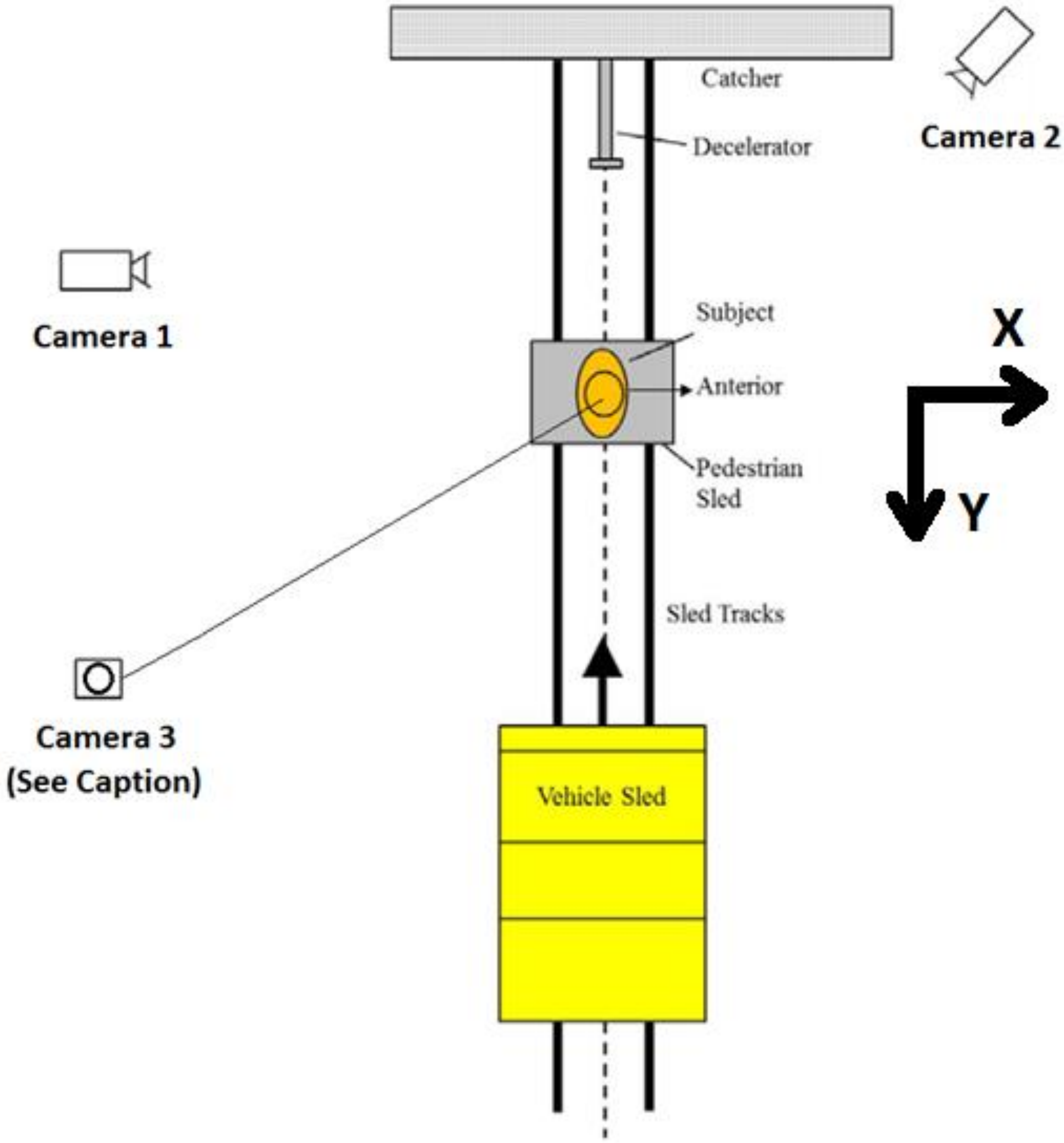

Figure 4: The location of the cameras used for the Model Based Image Matching with global coordinate system indicated (Positive Z-direction going into page). Note that camera 3 was located directly above the cadaver subject.

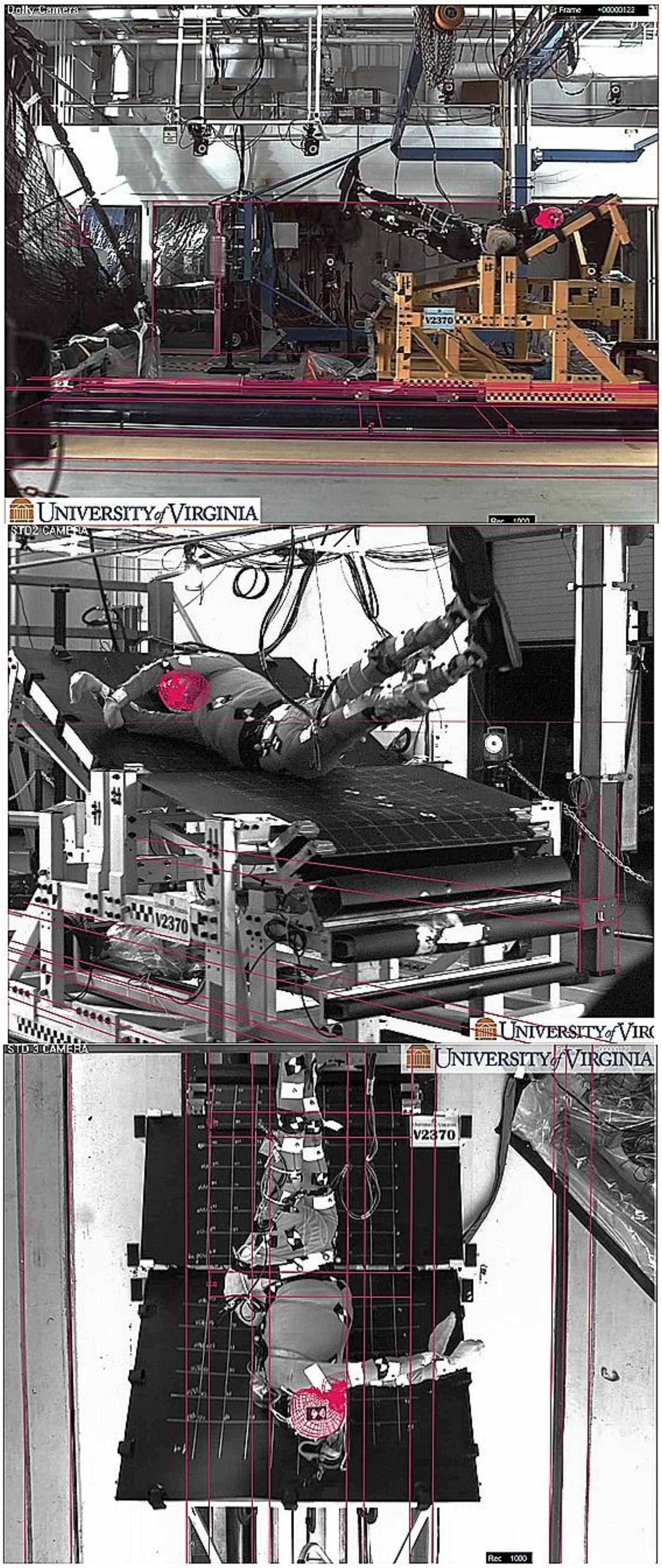

Figure 5: An example of the MBIM skeleton matching with the background video for frame 1 for (a) Camera 1, (b) Camera 2 and (c) Camera 3.

While the Vicon cameras recorded at 1000 fps, the MBIM was only conducted using 100 fps video, which is typical of uncompressed broadcast video (Collins & Evans, 2012). This approach yielded MBIM based head linear/rotational position measurements every 10 ms (known as a key frame). Similar to Krosshaug and Bahr (2005), cubic splines were fitted to interpolate between these discrete head linear/rotational position measurements.

Similar to the reflective marker-based data, the time derivatives of the yaw, pitch and roll angles were calculated using the Matlab gradient function and Equation 1 was used to define the components of the body local angular velocity vector of the head. The results from the linear and rotational tracking of the head position and velocity from the reflective marker-based system were then compared to the MBIM predictions.

Statistical Analysis

Similar to Mok et al. (2011), the differences between the reflective marker-based motion analysis and MBIM technique time histories were quantified using Root Mean Square Error (RMSE) and Intra-class correlation coefficients (ICC) were calculated to assess the intra-rater reliability and inter-rater reliability. To allow the RMSE calculations to be conducted, the MBIM data was up-sampled (based on the cubic spline interpolation method mentioned above) to 1000 Hz. Due to the MBIM technique providing continuous joint angle time-histories, two-way mixed model average ICC measures were calculated to evaluate reliability (Hopkins, 2000). ICC coefficients greater than 0.90 are indicative of excellent reliability (Mok et al., 2011). Since researcher R1 conducted the MBIM analysis three time for intra-rater repeatability, researcher R1's first analysis was used for the inter-rater repeatability ICC calculation.

Results

Validity

Figure 6 shows the MBIM head CG displacements and linear velocities in the global coordinate system (Figure 1) compared to the reflective marker-based results. Figure 7 shows the corresponding successive rotation angles and angular velocities compared to the reflective marker-based results. The head impact with the windscreen lasted for 14 ms (between 8 and 22 ms).

For head linear displacement the RMS error was under 20 mm for all displacements and 0.01-0.04 rad for head successive rotations (yaw, pitch and roll) (Table 2). For velocities, the MBIM method yielded RMS errors of 0.42-1.29 m/s for head linear velocities and 3.53-5.38 rad/s for head angular velocities (Table 2).

Inter-rater reliability and intra-rater reliability

For both inter-rater and intra-rater reliability, ICC coefficients greater than 0.94 were demonstrated for all parameters excluding linear velocity in the X-direction (0.501 & 0.409 respectively), see Table 3.

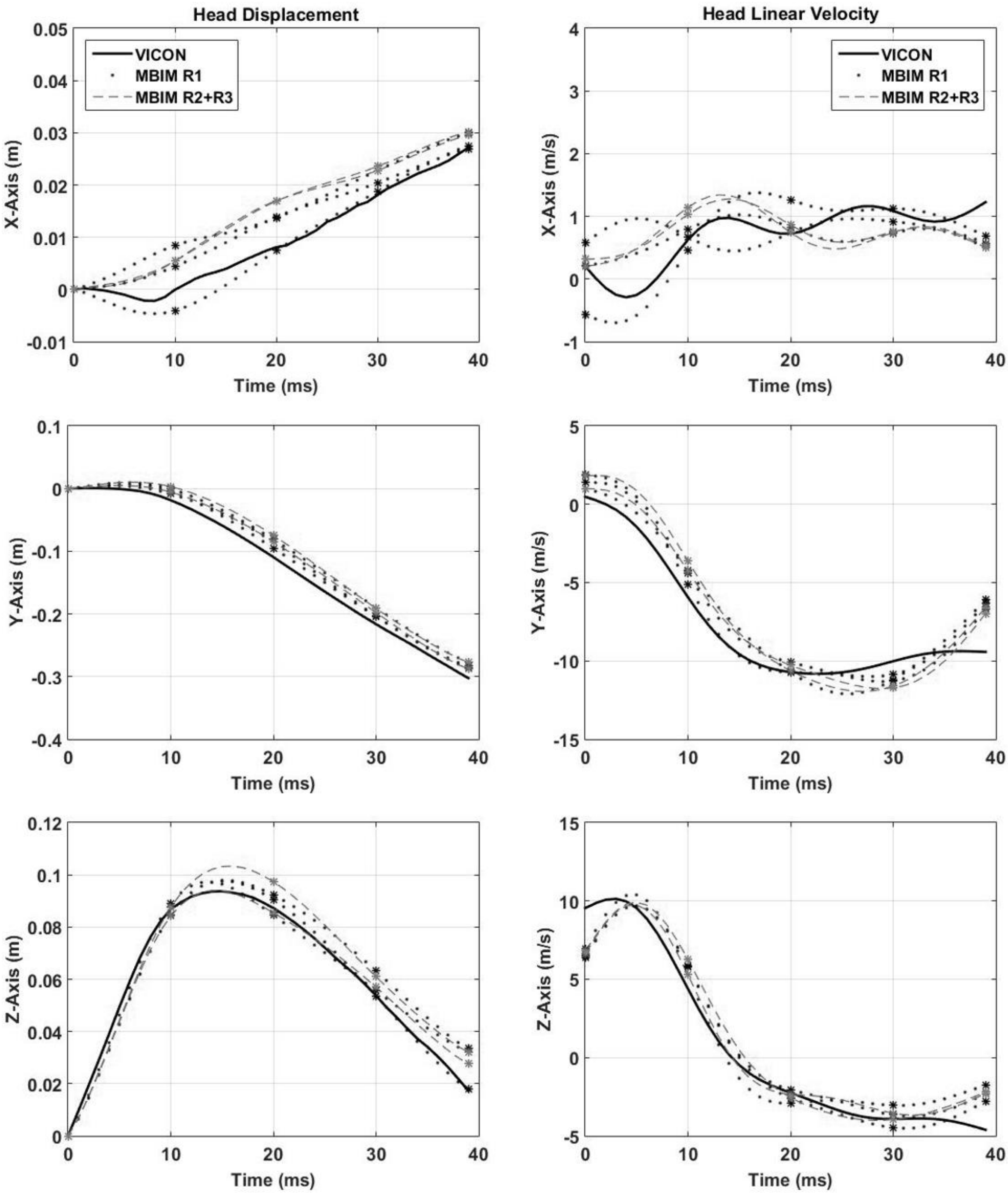

Figure 6. Head CG displacement (a-c) and linear velocity (d-f) in the global coordinate system (Figure 4) calculated with the reflective marker-based motion analysis (Black line) and the model-based image-matching technique for Researcher 1 (R1) (Grey dotted lines) and Researcher 2 (R2) and 3 (R3) (Grey dashed lines). The MBIM discrete measures are indicated with markers.

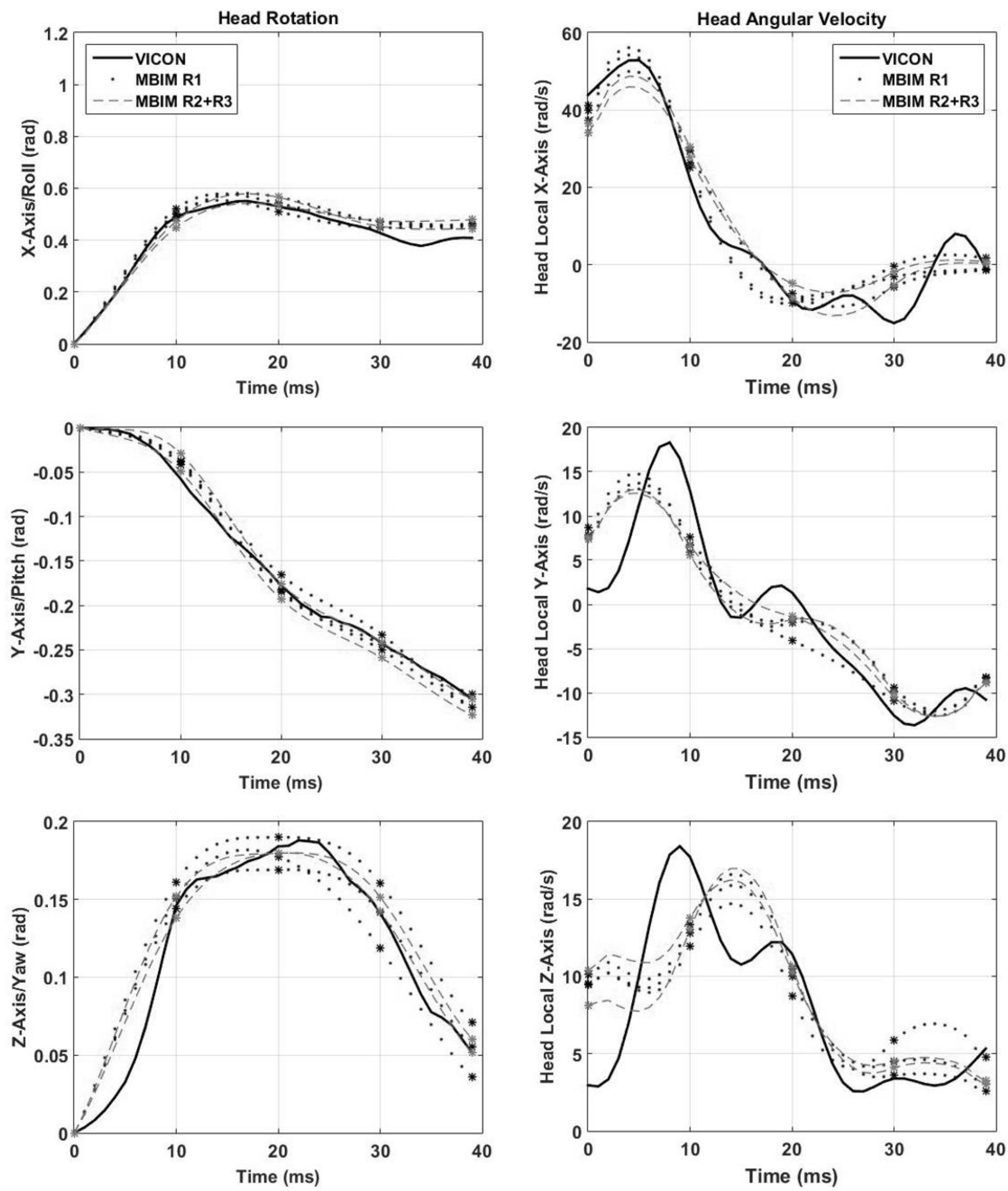

Figure 7. Head CG rotation for Roll (X), Pitch (Y) and Yaw (Z) angles (a-c) and the head angular velocity about the local head axes (d-f), see Figure 3, calculated with the reflective marker-based motion analysis (Black line) and the model-based image-matching technique for Researcher 1 (R1) (Grey dotted lines) and Researcher 2 (R2) and 3 (R3) (Grey dashed lines). The MBIM discrete measures are indicated with markers.

		Linear Displacement (m)	Linear Velocity (m/s)	Rotation (rad)	Angular velocity (rad/s)
X					
	RMSE	<0.01	0.42	0.04	5.38
	SD of RMSE	0.001	0.07	0.005	0.30
	Vicon Range	0 to 0.03	-0.29 to 1.23	0 to 0.55	-12.3 to 51.6
Y					
	RMSE	<0.02	1.29	0.01	4.10
	SD of RMSE	0.005	0.21	0.002	0.15
	Vicon Range	0 to -0.30	-10.82 to 0.48	0 to -0.31	-13.4 to 13.9
Z					
	RMSE	<0.01	1.07	0.02	3.53
	SD of RMSE	0.002	0.10	0.004	0.25
	Vicon Range	0 to 0.09	-4.61 to 10.13	0 to 0.19	0.37 to 15.5

Table 2: The Root Mean Square Error (RMSE) and Standard Deviation of the RMSE values for the MBIM measures compared to reflective marker-based system along with the range of reflective marker-based motion and kinematics values.

		Inter-rater repeatability	Intra-rater repeatability
Displacement			
	X	0.961	0.951
	Y	0.999	0.999
	Z	0.992	0.985
Linear Velocity			
	X	0.501	0.409
	Y	0.991	0.994
	Z	0.996	0.991
Rotation			
	X	0.994	0.994
	Y	0.999	0.997
	Z	0.996	0.982
Angular Velocity			
	X	0.992	0.988
	Y	0.998	0.989
	Z	0.985	0.943

Table 3: Intra-class correlation results for inter-rater reliability and intra-rater reliability.

Discussion and Implications

General

The aim of this study was to establish whether Model-Based Image-Matching (MBIM) is suitable for estimating 6DOF head displacement and velocities during a head impact event (similar to the kind experienced in unhelmeted sports, see Table 1) for which several camera views are available. Figures 6 & 7 and Table 2 show that the 6 degree of freedom head displacement time histories are accurately tracked (RMS errors less than 20 mm for linear displacement and less than 0.04 rad for rotational displacement). For multibody simulations, this is a significant advance on previous visual approaches used to estimate initial impact positions (Fréchède & McIntosh, 2007; Frechede & McIntosh, 2009; McIntosh et al., 2014). Furthermore, the inter-and intra-rater results indicated that the analysis was repeatable by both a single researcher and multiple researchers for six degree of freedom head positional data. The repeatability of linear velocity in the X direction was relatively low. The linear velocity of the head in the X direction was small meaning the ICC calculations were more sensitive to differences in rater measurements even though the absolute errors between rater measurements were low.

The assessment of the linear and rotational velocity predictions from the MBIM show substantially larger errors, particularly for angular velocity (RMS errors up to 5.38 rad/s). This means that the predictive capacity of the MBIM for angular velocity in this case is not very strong. Therefore, although the approach does provide an estimate of angular velocity, which previous video analysis approaches did not (McIntosh et al., 2000; Newman et al., 1999; Pellman et al., 2003; Viano et al., 2007), it remains difficult to measure this parameter accurately.

The Vicon cameras recorded at 1000 fps whereas the MBIM was conducted on 100 fps video as this is typical of uncompressed broadcast video (Collins & Evans, 2012). The results show some significant discrepancies in the Y and Z axis angular velocity results (Figure 7e-f & Table 2) even though the RMSE errors for the successive rotation angle results are all <0.04

rad (Figure 7a-c and Table 2). The frame rate is an important consideration for this. Lower frame rate video can result in certain movements of the head going untracked. For example, Figure 7c shows for the Yaw angle that significant angle changes happen between the key frame at 0 ms and the next key frame at 10 ms. The resulting MBIM Z component of angular velocity is therefore poor at this stage. Unfortunately, a separate analysis using 200 fps video for the MBIM technique yielded poor results as the absolute rotation of the head between key frames was too small and resulted in operator error. Therefore, availability of higher frame rate video may not serve to improve angular velocity estimates using MBIM.

The RMS error results for the six degree of freedom head positional data in this study are similar to that achieved by Mok et al (2011), who validated the MBIM technique for assessing ankle joint angles for sprain injuries. Given the accuracy of the 6 degree of freedom position measurements and the inability to measure accurate angular velocities of the head, it is therefore proposed that MBIM is beneficial to directly and reliably measure six degree of freedom head positional data from video of sporting head impacts. This MBIM data, combined with six degree of freedom velocity and acceleration data gained from wearable sensors (Wu et al., 2016), could be used in future to give accurate initial conditions and further evaluate the outputs of multibody and finite element head model simulations of sporting head impacts. The technique might also help to evaluate wearable head impact sensors, such as the instrumented skin patch and mouthguard, by providing an independent direct measurement of six degree of freedom head positional data to compare against (Wu et al., 2016).

Limitations

In this paper, the MBIM method was only applied to a single head impact since there was only one case with suitable video available. While the cameras in this case were positioned closer to the impact subject than in a sporting collision, zoomed in replays offering close-up views of head impacts are often available in sport (Tierney, Krosshaug, & Simms, 2015) and the head actually did not account for a large number of pixels in the videos used for this study (24x28 pixel in Camera 1, 45x44 pixels in Camera 2 and 67x55 pixels in Camera 3). The resolution for each video was 800x600 pixels, which is less than standard HD video quality (1280x720) (Alvarez, Salami, Ramirez, & Valero, 2007).

Certain recognisable facial features on the cadaver such as the eyes and ears could not be seen in this case, see Figure 2. This made the matching more difficult as rotational tracking was only possible based on the identification of the nose and mouth of the cadaver, although the Vicon markers compensated for this.

In this study, there were a number of references in the background video which were suitable for constructing the virtual environment for the MBIM approach. In most unhelmeted sports, such as Rugby, there are a large number of field lines and markings, as well as goal posts and advertising boards which can be used to build the virtual environment necessary for the MBIM reconstruction. The cameras were stationary in this study which is untypical of broadcast sports video. The MBIM technique can still be conducted on non-stationary cameras by readjusting the camera positioning tool for each key frame.

In sporting applications, the number of camera views available will vary. An initial analysis using only two camera views yielded poor results when compared to the reflective marker-based data. The accuracy of 3 camera views for the MBIM method in this case may be partly due to Camera 1 and Camera 3 being almost perpendicular (Figure 4) to each other and thus reducing out of plane errors. It is recommended that perpendicular views are selected for the MBIM method whenever possible.

The MBIM method is currently a time-consuming process as it requires manual frame-by-frame matching (approximately 40 hours in this case). Further work should look at automating this technique.

Conclusions

The comparison of the MBIM approach to the reflective marker-based system measurements shows good ability of the method to record head linear and rotational positional data in an impact event which caused significant head motion. However velocity data was less accurate, particularly for angular velocity and increased frame rate video did not improve this. The MBIM method could be used in future as a tool to directly and reliably measure six degree of freedom head positional data, which can be combined with wearable sensor velocity and acceleration data, to give accurate initial conditions and further evaluate the outputs of multibody and finite element head model simulations of sporting head impacts. The inter-and intra-rater results indicate that the analysis was repeatable by both a single researcher and multiple researchers for six degree of freedom head positional data.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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