Università degli Studi di Padova
DEI – Dipartimento di Ingegneria dell'Informazione

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# Studio della cinematica di traumi al cervello riscontrabili durante incontri professionistici di boxe

Kinematic evaluation of traumatic brain injuries in boxing

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# Abstract

Motion tracking, based only on analysis of videos broadcasted by television, is evaluated as a method to assess the kinematics of a mild traumatic brain injury during a professional boxing match. A database composed of 25 knockouts and 10 other major hits, divided in subgroups according to the frame rate of the cameras used to record the matches, was selected and analyzed using a proper motion tracking software. Magnitudes of translational and rotational velocities and acceleretions of the hand of the boxer throwing the punch and the head of the opponent were taken into consideration and compared with values found in previous studies of sports-related concussions to get an evaluation of the effectiveness of the method. Data obtained from knockouts recorded at 90 fps (frames per second) were comparable with the ones found in literature: an average maximum value of head rotational acceleration equal to 8783 rad/s$^2$ (SD 2290 rad/s$^2$) and a mean HIC equal to 303,5 (SD 287,8). A significant dependence of the peak values on the sample frequency of the videos was noticed. Values related to punches recorded at a frame rate lower than 90 fps were much lower and therefore not comparable. A difference between peak values regarding knockouts and other hits was found but the database was too small to make it statistically significant. In conclusion, this method to evaluate the kinematics of sports-related MTBIs is effective even though some precautions should be taken in order to obtain more precise results.

Key words: kinematics, motion tracking, video analysis, traumatic brain injury, concussion, boxing, head rotational acceleration.

# 1. Introduction

Nowadays head injuries are one of the leading causes of disability and mortality in many parts of the world. In the United States nearly 2 millions traumatic brain injuries (TBIs) cases occur each year [1]. They are responsible for 50 thousands deaths and approximately 275 thousands hospitalizations [2,3]. TBIs are not only a serious issue for the people involved but also place an enormous burden on society in terms of a social, economical and emotional price. Most of them are the result of car accidents and motorcycle crashes and, since there is no proper cure at this time, the best thing to do is trying to prevent and minimize these injuries. In order to do that, a complete understanding of injury mechanism, response and tolerance level is required.

An increasing number of brain injuries related to recreational sports such as boxing, American football and hockey, has been recorded, even when protective devices are in use. In this case, injuries are usually, but not always, not too severe and are referred as “mild traumatic brain injuries” (MTBIs) or concussions.

Cerebral concussions are the most relevant consequence of boxing as the explicit objective of a boxing match, fought according to the rules, is to render the opponent unable to defend himself, for example, by inflicting him a blunt head injury with subsequent intermittent loss of consciousness (knockout) [4]. In a 16-year-long study [5] of injuries to professional boxers in Australia, 107 injuries were reported in 427 fights participations from August 1986 through to August 2001. The most commonly injured body region was the head and neck (89,9%) and 15.9% of these injuries were concussions.

Unfortunatly, MTBIs are not the only injuries an athlete can suffer on a boxing ring and records [6], kept since 1890 about matches fought according to different rules, have documented about 10 deaths every year. Actually these records are not complete so the real number is likely to be even higher.

Looking at these numbers, it is glaring that a complete understanding of head impacts is essential in order to reduce the probabilty and the amount of damage suffered by the athlets. In spite of that, traumatic injury has not been studied extensively and the reason is quite obvious: one cannot willingly espose a live human being to a potentially injurious blow to the head. So nowadays most of what is known has been established from experiments with surrogates, such as animals, cadavers, and in a few cases volunteers [7,8] and dummies.

However, mild traumatic brain injuries from boxing matches provide a sort of "living laboratory" to study concussion mechanisms and tolerance levels in human beings, with possible extrapolation to the general population.

The aim of this study is to perform a biomechanical examination of a head trauma based only on video analysis of television footage of the boxing match. The results of the analysis are then used to determine if these videos are actually good enough, in terms of frame rate and resolution, to perform it. They are also compared to the results obtained in previous studies that used different methods to achieve the same analysis.

## 1.1 Mild Traumatic Brain Injury

Several definitions have been given to traumatic brain injury based on different criteria. TBI is a non-degenerative, non-congenital insult to the brain from an external mechanical force, possibly leading to permanent or temporary impairment of physical, cognitive and psychosocial functions, with an associated diminished or altered state of consciousness.

Parameters such as severity, anatomical features of the injury and the mechanism of the forces are usually used to classify TBIs.

Referring to the severity, we can use three scales to divide traumatic brain injuries in mild, moderate and severe:

- The Glasgow Coma Scale (GCS), which evaluates the level of consciousness of the victim.
- The duration of post-traumatic amnesia (PTA).
- The loss of consciousness (LOC).

| | **GCS** | **PTA** | **LOC** |
|---|---|---|---|
| **Mild** | 13-15 | < 1 day | 0-30 minutes |
| **Moderate** | 9-12 | > 1 to < 7 days | > 30 minutes to < 24 hours |
| **Severe** | 3-8 | > 7 days | > 24 hours |

**Table 1.** TBI Classification

From Table 1 we can get an idea of what a mild traumatic brain injury (MTBI), or “concussion”, is.

A concussion is a physical injury to the head resulting in altered mental function, with expectation of recovery within 2–3 weeks. In a significant minority of cases the symptoms persist longer, thereby comprising a group of symptoms commonly referred to as the “post-concussion syndrome”, that is, one or more somatic (for example, headaches, dizziness), cognitive (for example, poor concentration, memory), or behavioral/affective (for example, irritability, mood swings) symptoms [9].

MTBI has been given more than one definition. We use the following, by the Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group of the American Congress of Rehabilitation Medicine [10]:

"*A patient with mild traumatic brain injury is a person who has had a traumatically induced physiological disruption of brain function as manifested by at least one of the following:*

*1. Any period of loss of consciousness;*

*2. Any loss of memory for events immediately before or after the accident;*

*3. Any alteration in mental state at the time of the accident (e.g., feeling dazed, disoriented, or confused);*

*4. Focal neurological deficit(s) that may or may not be transient but where the severity of the injury does not exceed the following:*

*A. loss of consciousness of approximately 30 minutes or less;*

*B. after 30 minutes, an initial Glasgow Coma Scale (GCS) of 13-15;*

*C. post-traumatic amnesia (PTA) not greater than 24 hours."*

According to this definition, in this study it was decided to consider "concussed" the boxers who, after a punch to the head, looked dizzy and could not stand on their feet without losing their balance after a count of ten by the referee.

This means the end of the match by knockout (KO), in most cases, or by technical knockout (TKO) after a short time in a few other cases.

During the last three decades more than 8 classification systems [11] have been proposed for concussions (MTBIs) with disagreement and differences regarding terminology and symptoms priority. All of them were based on experimental theory and not on scientifically proven research. No classification system has been established as superior.

However lately three classification schemes have been accepted in widespread application:

- Cantu guidelines [12], based on persistence of memory disturbance (amnesia).
- Colorado Medical Society guidelines [13].
- American Academy of Neurology guidelines [14].

The following table delineates the concussion classification schemes of the three guidelines:

| Concussion Grade | Cantu | CMS | AAN |
|---|---|---|---|
| Grade 1 – Mild | No LOC and Post-traumatic amnesia < 30 mins | No LOC, Post-traumatic confusion, No post-traumatic amnesia | No LOC, Post-concussive symptoms last < 15 mins |
| Grade 2 – Moderate | LOC < 5 mins or Post-traumatic amnesia > 30 min and < 24 hrs | No LOC, Post-traumatic amnesia | No LOC, Post-concussive symptoms last >15 mins |
| Grade 3 - Severe | LOC > 5 mins or Post-traumatic amnesia > 24 hrs | Any LOC | Any LOC |

**Table 2.** Concussion Classification

The loss of brain functions associated with a concussion (see Table 2 above) is supposed to be due only to physiological changes, not structural, but this point is still not clear [15].

From a mechanical point of view, a MTBI is the result of an impact force, that means the head is struck by something (this is the case also in boxing matches), or an impulsive force, that means the head moves but is not actually subject to a blunt trauma. This force causes movements of the brain, which usually are a combination of linear, rotational (the head turns around its center of gravity) and angular (it turns on an axis not through the center of gravity) motions [9].

When the linear acceleration of the center of gravity, but even more importantly, the rotational acceleration of the head is excessive (like in occasion of a hook during a boxing match) the motion of the brain lags that of the skull (Figure 1) and the brain distorts [16].

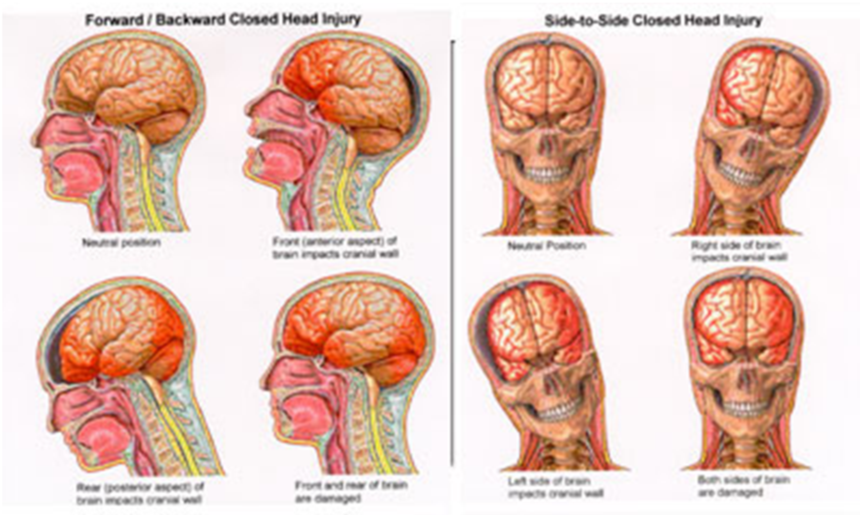


**Figure 1.** Movements of the brain inside the skull after an impact

Because of this distortion, neurological disfunctions, like the ones previously described, will be subsequently observed.

Additionally, impact of the brain hemispheres against the roof of the skull may cause coup and countercoup lesions as a result of punches to the head or the head striking the ring floor after a fall of the athlete.

## 1.2 Previous studies

Many studies can be found in the literature about the mechanical analysis of concussions in sports. They are not only from boxing matches but also from American football and ice hockey [17]. This means their results can be compared with the ones of this study but doing that we have to keep in mind the significant differences between these sports because they directly reflect on the result. For example, the most obvious difference is the use of protective helmets by hockey and football players.

A pioneer study that used volunteer boxers is the one by Chamouard et al. (1987) [7]. The purpose was to evaluate direct head impacts in boxing just because these impacts were similar to those experienced by vehicle occupants under crash conditions.

A device for the hand of the attacker and a sort of helmet for the athlete receiving the blow were provided with different accelerometers in order to measure the different components of the motion (Figure 2).

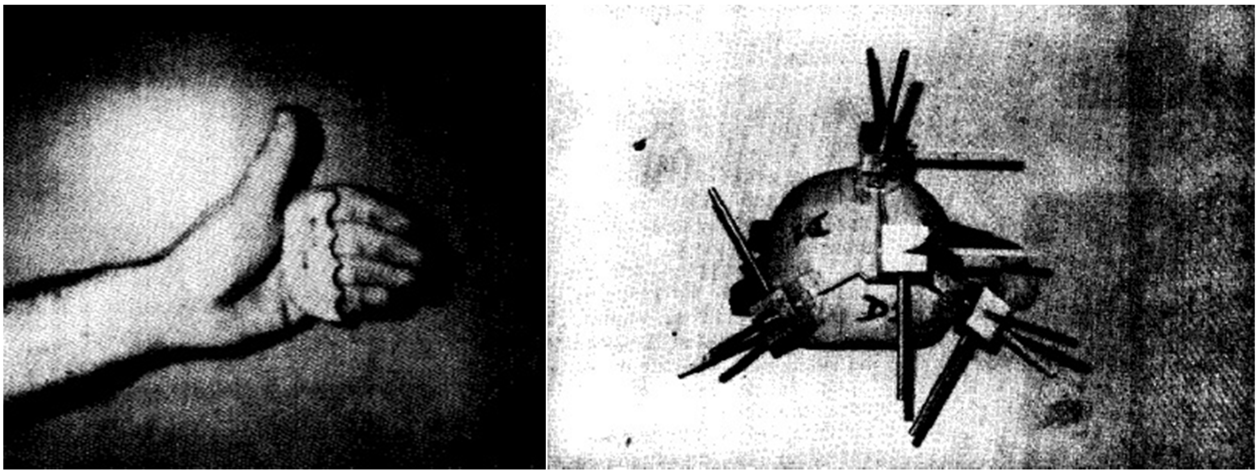

**Figure 2.** Hand device and head gear with accelerometers [7]

After that, the resultant linear velocity, linear acceleration, angular velocity, angular acceleration and HIC (Head Injury Criterion) value of the head were calculated. Finally some tests were run on the struck boxers to check their brain response to different stimulations. Thanks to this study, it has been possible to get an idea of the order of magnitude of the values previously mentioned but obviously no volunteer was intentionally concussed so it was not possible to estimate a sort of "threshold", for example, for the rotational acceleration value, to tell us whether a concussion happens or not.

Lately, many other studies were performed in order to evaluate the biomechanics of the head during boxer punches. Two examples are the work by Beckwith et al. (2007) [18] and the work by Walilko et al. (2004) [19]. Both of these are based on the use of dummies.

The first one is a validation of a non-invasive measuring system for head acceleration fitted inside a boxing headgear. Even if in the future this could help us find the values we are looking for, so far this device is not yet in use.

In the second study, instead, one single heavyweight boxer was asked to throw "normal punches" to a dummy head fitted with several accelerometers (Figure 3).

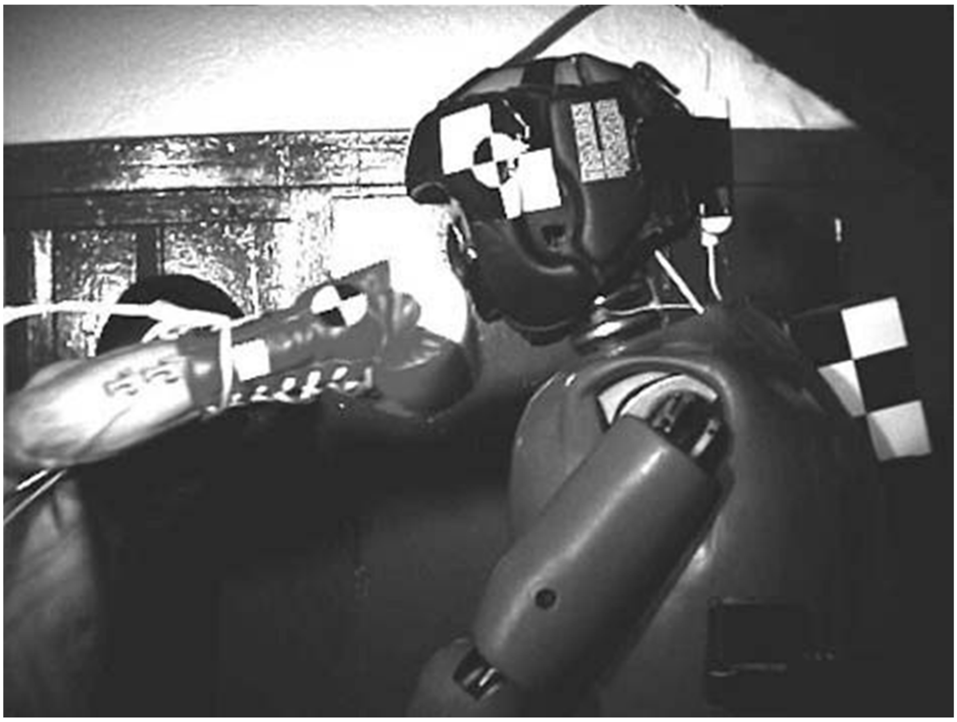

**Figure 3.** Olympic boxer throwing straight right punch to jaw region of instrumented Hybrid III dummy [19]

From this experiment it was possible to get the average values of hand velocity (9.14 (SD 2.06) m/s), peak translational acceleration of the head (58 (SD 13) g). peak rotational acceleration of the head (6343 (SD 1789) rad/$s^2$) and HIC (71 (SD 49) g). Also in this case it is not possible to say if the values relating to these “normal punches” are above a certain threshold to result in a concussion during a match or if they are not.

In order to get values on concussions specifically, we have to rely on other studies which are about American football.

One example is the work of Zhang et al. (2004) [20] based only on a part (24 cases out of 58) of the data previously produced by Newman et al. (2000) [21]. In this study, an attempt was made to delineate the concussion mechanisms and establish a meaningful injury criterion through the use of actual field data. An accident reconstruction using an anatomically datailed model was performed to predict the extent and severity of brain response as a consequence of a particular impact. Therefore, the appropriate injury predictors based on this response could be used to establish a variety injury tolerance levels by a statistical approach. This kind of approach was completely different from most of the previous studies which proposed tolerance levels based on imput kinematics either scaled from animal data or noninjurious volunteers test results. To reconstruct the heads collisions, two dummy heads wearing football helmets fitted with nine linear accelerometers were attached to two dummy necks: one of them (representing the struck player) was mounted on a rigid base and the other one (representing the striking player) on a vertical twin-wire guided free-fall system.

The velocity of one player’s head relative to the other was determined through frame-by-frame video analysis of the match, then the “striking head” was raised to an appropriate height so that upon release it fell freely and attained the desired impact (Figure 4).

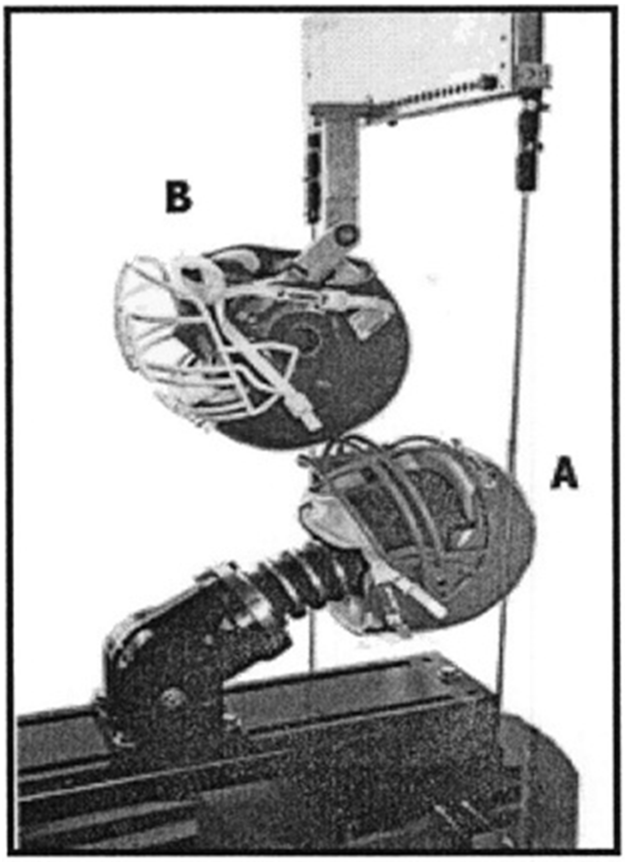


**Figure 4.** Laboratory accident reconstruction set up:
A represent struck player's head
B represents striking player's head [20]

These are the mean peak values, relative to the struck head, result of this experiment:

- Translational acceleration: 103 ± 30 g injured, 55 ± 21 g non-injured.
- Rotational acceleration: 7354±2897 rad/s$^2$ injured, 4204±1411 rad/s$^2$ non-injured.
- HIC: 441±224 injured, 137±124 non-injured.

The subsequent elaboration of the data had also implied either a translational but more importantly a rotational acceleration as essential elements for an injury to occur.

The "threshold values" related to the probability of a concussion to occur are shown in the following table and figure:

| Probability of MTBI | CG Translational Acceleration (g) | Rotational Acceleration (rad/s²) | HIC |
|---|---|---|---|
| 25% | 66 | 4600 | 151 |
| 50% | 82 | 5900 | 240 |
| 80% | 106 | 7900 | 369 |

**Table 3.** Estimated threshold values in relation of the probability for a concussion to occur

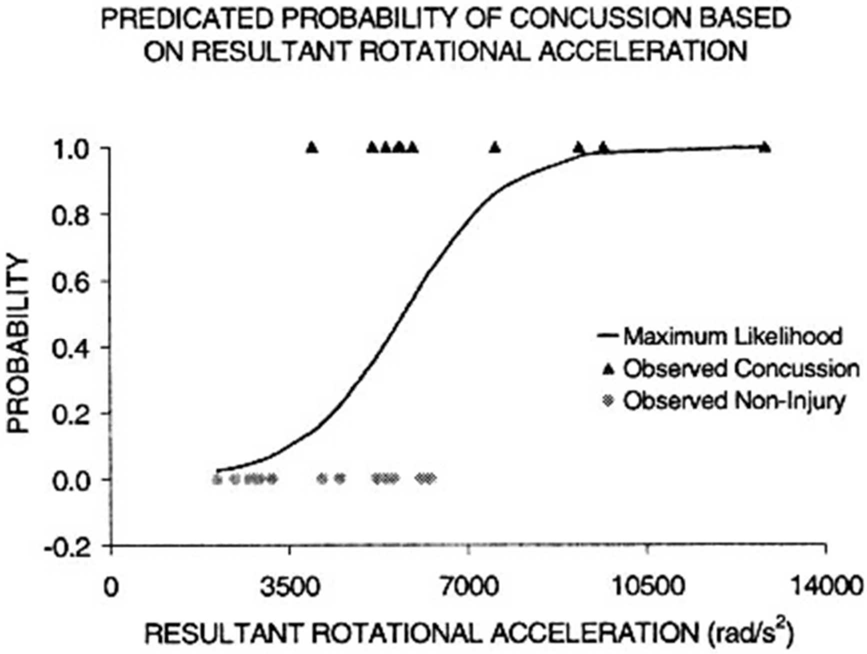


**Figure 5.** Predicted probability of MTBI based on rotational acceleration of the head [20]

In 2005, Newman et al. published another study [16] based on the same data set and very similar to the previous one regarding the laboratory set up. This time, in addition, two systems, one based on a pendulum and one on complete instrumented test dummies (Figure 6), were used to investigate how accurately the overall laboratory re-enactment set up worked.

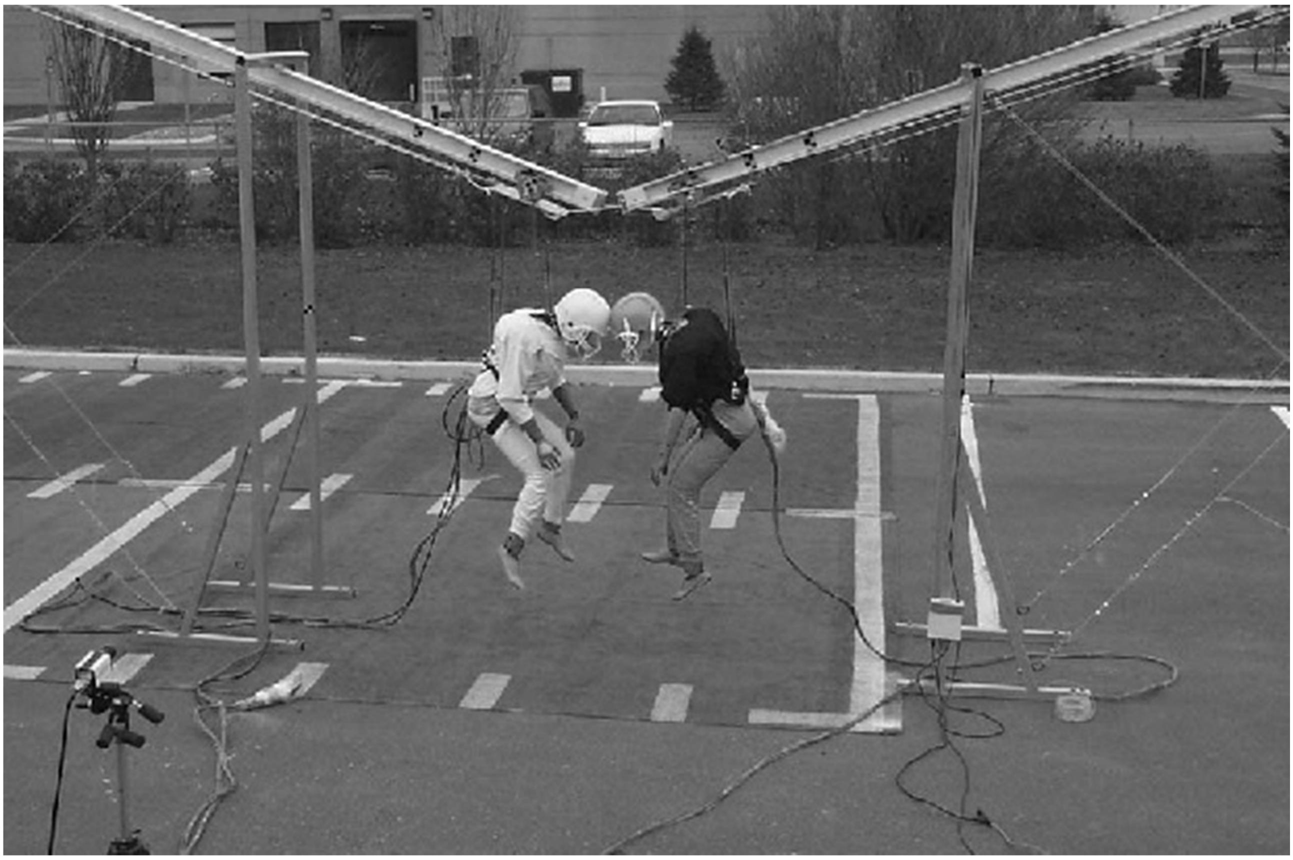

**Figure 6.** Full scale simulation of an actual game collision [16]

The following average results were obtained:

- Translational acceleration: 959 $m/s^2$ (98 g) injured, 557 $m/s^2$ (57 g) non-injured.
- Rotational acceleration: 6432 $rad/s^2$ injured, 4028 $rad/s^2$ non-injured.

Kleiven (2007) [22] was the first one to analyze all the 58 NFL cases collected by Newman [21] using a detailed and extensively validated finite element model of the human head in order to evaluate different predictors for concussion. The results of this study state that the translational kinematics was the most important factor for the intracranial pressure while the rotational kinematics was the most important one for the intracranial deformation. In fact the correlations with the distortional strain, as well as injury, of the resultant rotational accelaration (R=0,84) and the resultant peak change in rotational velocity (R=0,78) were found to be higher than the ones of the resultant translational acceleration (R=0,65) and HIC (R=0,61). Finally, a simple linear combination (Figure 7) of peak change in rotational velocity and HIC showed an even higher correlation (R=0,98).

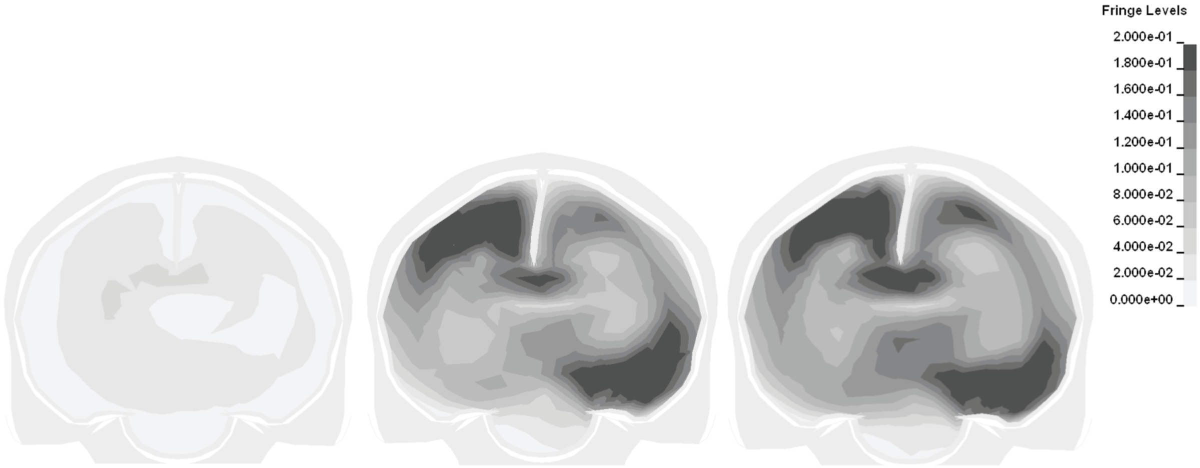


**Figure 7.** Strain distribution in a coronal plane when applying only translational or rotational kinematics and for the application of the full kinematics for one of the 58 NFL cases [22]

The last study about concussions in American football worth reporting is the one by Pellman et al. (2003) [23]. It is based on a very large amount (182) of videos of severe helmet impacts filmed between 1996 and 2001 in the National Football League. It shows an average peak head translation acceleration of 98 ± 28 g for injured players and 60 ± 24 g for non-injured players. It also sets a nominal tolerance level of a HIC equal to 250 for a MTBI.

## 1.3 A brief introduction to the method

The method used in this study is basically different from all the ones mentioned before and could be an alternative to performing mechanical analysis of head trauma and brain injury.

Being based only on video analysis, in fact, it could be executed without the need of any particular “hardware” as dummies or accelerometers or free-fall systems: just a couple of cameras and a computer would be enough to perform the whole analysis. This obviously could save time and money.

We selected 35 videos from a DVDs collection taken from television shootings in the last thirty years and analysed them with a software called SkillSpector, which allowed us to execute a three dimensional motion tracking of the head of the hit boxer and of the arm of the attacker.

The fact that these are television footages is actually very important in the evaluation of the results. We did not have any match recorded with high speed cameras so the only way to get a frame rate higher than the usual television one (30 or 25 frames per second) was to use the slow motion replays.

The set-up of one video analysis briefly consisted in:

- Choosing at least two (the minimum needed for a three dimensional analysis) different camera angles so that a good view of the athletes and of some kind of angular references was ensured.
- Selecting, from the chosen views, only the few frames in which the hit was shown making sure that they matched in terms of timing of movement.
- Achieving a “virtual calibration” to set the axis, needed for the analysis, taking into consideration references as the ropes, the ring posts, the head or other body parts of one of the two boxers.

After the analysis, the data were elaborated using some Matlab functions and comparisons were made between the values:

- First of all, we checked if our data were comparable, considering errors, with data previously found in literature.
- Then, data relative to concussions were compared with data relative to other not so severe hits.
- Finally, results from same kind of hits were compared according to the value of fps (frames per second) of the video from which they were taken.

With these results we tried to estimate if our method was reliable to perform a mechanical analysis of a head trauma during a boxing competition and in which cases it was.

# 2. Video analysis and motion tracking

After viewing a large number of DVDs and internet videos of professional boxing matches, the best 35 punches to the head, in terms of image quality and camera angles, were selected.

The hits were classified in two categories, based on the results of the shot on the struck boxer:

- Knockouts:
    1. he was not able to stand on his feet before a count of ten (KO);
    2. he managed to get up on his feet before a count of ten but he looked too dizzy and the referee stopped the match (TKO);
    3. he did not fall on the canvas, most of the time because he was standing between his opponent and the ropes, but he looked unconscious and unable to defend himself so the referee stoped the match (TKO).

- Other hits: he did not fall on the canvas or he did but he was able to get back on his feet before a count of ten and the match could continue. In some of these cases (4 of 10), though, there was no count by the referee as the match was stopped shortly after the analyzed punch because that was followed by several others, more severe, which led to a KO or a TKO.

The set of hits included 25 Knockouts and 10 Other Hits.

In the next pages two lists, KOs (Table 4) and Other Hits (Table 5), of the selected matches, complete with dates, weight and current weight division of the athletes, are available.

The numbering of the matches is kept in all the other subsequent tables of the study results.

| Match Number | KO Type | Striking Boxer | Weight (Kg) | Struck Boxer | Weight (Kg) | Weight Division | Date of the Match |
|---|---|---|---|---|---|---|---|
| 1 | KO | Arguello | 63.6 | Rooney | 63.5 | Junior Welterweight | 31 Jul 1982 |
| 2 | KO | Currie | 105.2 | McCrory | 98.9 | Heavyweight | 07 Oct 1986 |
| 3 | TKO | Hopkins | 71.2 | Trinidad | 71.9 | Middleweight | 29 Sep 2001 |
| 4 | KO[1] | Maysonet | 67.1 | Kearney | 66.7 | Junior Middleweight | 28 Apr 1988 |
| 5 | KO | Kelley | 56.6 | Gayner | 57.2 | Featherweight | 15 Jun 1996 |
| 6 | TKO | Sheika | 76.2 | Sample | 74.8 | Super Middleweight | 29 Jul 1997 |
| 7 | KO | Johnson | 78.0 | Guthrie | 78.9 | Light Heavyweight | 06 Feb 1998 |
| 8 | TKO | Whitaker | 61.0 | Lomeli | 61.0 | Lightweight | 30 Apr 1989 |
| 9 | TKO | Vargas | 70.8 | Rivera | 70.8 | Middleweight | 05 May 2001 |
| 10 | KO[2] | Williams | 99.3 | Weathers | 98.8 | Heavyweight | 19 Mar 1996 |
| 11 | KO | Trinidad | 66.7 | Zulu | 66.7 | Welterweight | 03 Apr 1998 |
| 12 | TKO | Jackson | 72.6 | Cardamone | 72.6 | Middleweight | 17 Mar 1995 |
| 13 | KO | Bailey | 63.5 | Gonzalez | 63.4 | Junior Welterweight | 15 May 1999 |
| 14 | TKO | Tua | 101.2 | Izon | 101.6 | Heavyweight | 21Dec 1996 |
| 15 | KO | Tua | 114.3 | Chasteen | 112.0 | Heavyweight | 30 Nov 2002 |
| 16 | KO | Tua | 102.1 | Ruiz | 99.3 | Heavyweight | 15 Mar 1996 |
| 17 | KO | Helenius | 108.5 | Peter | 117.9 | Heavyweight | 02 Apr 2011 |
| 18 | TKO | Tackie | 62.1 | Garcia | 61.7 | Junior Welterweight | 03 Jun 2000 |
| 19 | KO | Tua | 112.0 | Nicholson | 101.2 | Heavyweight | 23 Mar 2001 |
| 20 | KO | Tyson | 102.4 | Etienne | 101.0 | Heavyweight | 22 Feb 2003 |
| 21 | KO | McCallum | 69.7 | Curry | 69.9 | Junior Middleweight | 18 Jul 1987 |
| 22 | KO | Lewis | 113.1 | Tyson | 106.1 | Heavyweight | 08 Jun 2002 |
| 23 | KO | Pacquiao | 62.6 | Hatton | 63.5 | Junior Welterweight | 02 May 2009 |
| 24 | TKO | Barkley | 78.9 | Hearns | 79.2 | Light Heavyweight | 20 Mar 1992 |
| 25 | TKO | Olson | 50.8 | Solis | n.a. | Flyweight | 30 May 1991 |

**Table 4.** KO Matches

[1] [2] Officially ruled as TKO by the referee who didn't even finish the count of 10 to end the match.

| Match Number | Result of the Hit | Striking Boxer | Weight (Kg) | Struck Boxer | Weigh t (Kg) | Weight Division | Date of the Match |
|---|---|---|---|---|---|---|---|
| 1 | TKO | Bowe | 104.3 | Tillery | 101.3 | Heavyweight | 13 Dec 1991 |
| 2 | Ref Count | Hopkins | 72.6 | Brown | 72.6 | Middleweight | 31 Jan 1998 |
| 3 | KO | Maysonet | 67.1 | Kearney | 66.7 | Junior Middleweight | 28 Apr 1988 |
| 4 | Ref Count | Sheika | 76.2 | Belanger | 76.7 | Light Heavyweight | 06 May 1997 |
| 5 | Ref Count | Trinidad | 69.9 | Vargas | 69.9 | Light Middleweight | 02 Dec 2000 |
| 6 | TKO | Tua | 101.2 | Maskaev | 105.6 | Heavyweight | 05 Apr 1997 |
| 7 | Ref Count | Judah | 62.6 | Millet | 63.3 | Junior Welterweight | 05 Aug 2000 |
| 8 | Ref Count | Trinidad | 69.9 | Vargas | 69.9 | Light Middleweight | 02 Dec 2000 |
| 9 | TKO | Lewis | 113.4 | Botha | 107.5 | Heavyweight | 15 Jul 2000 |
| 10 | Ref Count | Taylor | 64.0 | Gonzales | 64.0 | Welterweight | 09 Apr 1988 |

**Table 5.** Other Hits Matches

## 2.1 Set-up: video analysis, frame rate determination and elaboration

Some technical procedures were needed in order to get the videos ready for the actual motion tracking. First of all, we converted the DVD videos from the .vob format to the .avi format trying to use a codec which could give us the best results in terms of image quality (resolution). This step was necessary since the the subsequent software we used, VirtualDub, was not able to open a .vob file.

Once we got the video file of a single match in the proper format, we needed to extract only the few frames showing the hit to the head from the different cameras. Unfortunately, all the times we knew only the frame rate of the first camera because it was the one recording in real-time, i.e. at 25 or 29.97 frames per seconds, the other were slow motion replays at an unknown frame rate. So the first things to do was to determine the actual fps value of these replays.

In order to do that, we took into consideration a certain time lapse, usually from the beginning  of the movement of the arm throwing the punch until the hit of the opponent's head onto the canvas. We marked the frames from the different views ("first camera" and replays) where we could see the beginning and the end of this movement and we counted the number of frames. Then we simply calculated the ratio. It turned out that usually, except for a few cases, replays had a fps value equal to the double or the triple (2x or 3x) of the first camera's one.

After that, we could extract the sequence of frames in which only the blow was present, taking care of the exact matching, regarding the movements, of the first and the last frames from the different cameras. As mentioned, these cameras usually had different frame rates. Beacause of that, we had to "under sample" (Figure 8) the ones with higher fps in order to get the same number of frames, taken at the exact same moment, from all of them.

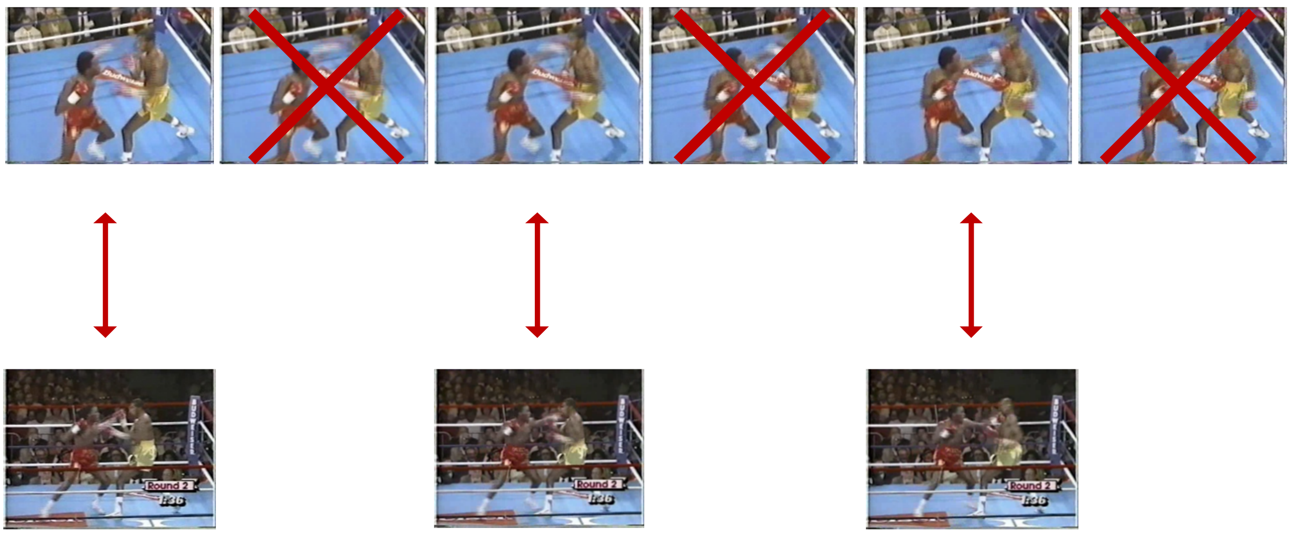

**Figure 8.** "Under  sampling" of frames from a 2x replay in order to have a correct match with the frames from the other camera (first row: 2x replay frames; second row: first camera frames)

Using again VirtualDub, we then produced one video for each camera view out of these frames sequences. After this we were finally ready for the motion tracking part of the study.

# 2.2 Motion tracking

To perform the motion tracking, a software called SkillSpector [24] was used. This is a very powerful tool, capable of producing a three dimensional video analysis of a movement and give us back relevant data like the position, the velocity and the acceleration, both linear and angular, of a certain set of points of our choice.

The procedure can be divided in three different phases:

1. The calibration of the videos.
2. The actual motion tracking.
3. The analysis of the results.

## 2.2.1 Choice of the cameras and calibration

As previously mentioned, the matches to be analyzed were chosen not only taking into consideration the resolution of the video but also the quality of the visual angles. It is important to have a good view of the striking boxer's arm and of his opponent's head to perform a reasonable motion tracking. At the same time a good view of some references, like the ring ropes and posts or advertising writings and logos, is essential to execute the calibration.

According to the software's documentation [24], an object with known dimensions should be recorded before or after the main video in the same place, with the same cameras and at the same angles used in the footage of the movement. Since we did not have such an object, we chose a “reference object” that was visible from each camera. We then calculate its size and used it to perform a sort of “a posteriori calibration”.

The easiest way to do that was to use a ring post as a reference. In fact, even if the ring size may change, depending on the type of match and on the boxing federation, the distance between the ropes, i.e. 1 foot (0.3048 m), is always the same for a ring with four ropes [25]. Furthermore, the ropes attached to the ring post are perpendicular to each other and to the post itself so a good x,y,z three-dimensional coordinates system (Figure 9) can be obtained avoiding large errors on the angles.

As a result, we simply needed to calculate with a 3D-image editing software [26] the correct length of the segments seen in perspective.


**Figure 9.** Calibration with a ring post as a reference

At least six points, i.e. five segments, with known coordinates, were needed to execute the calibration (Figure 10).

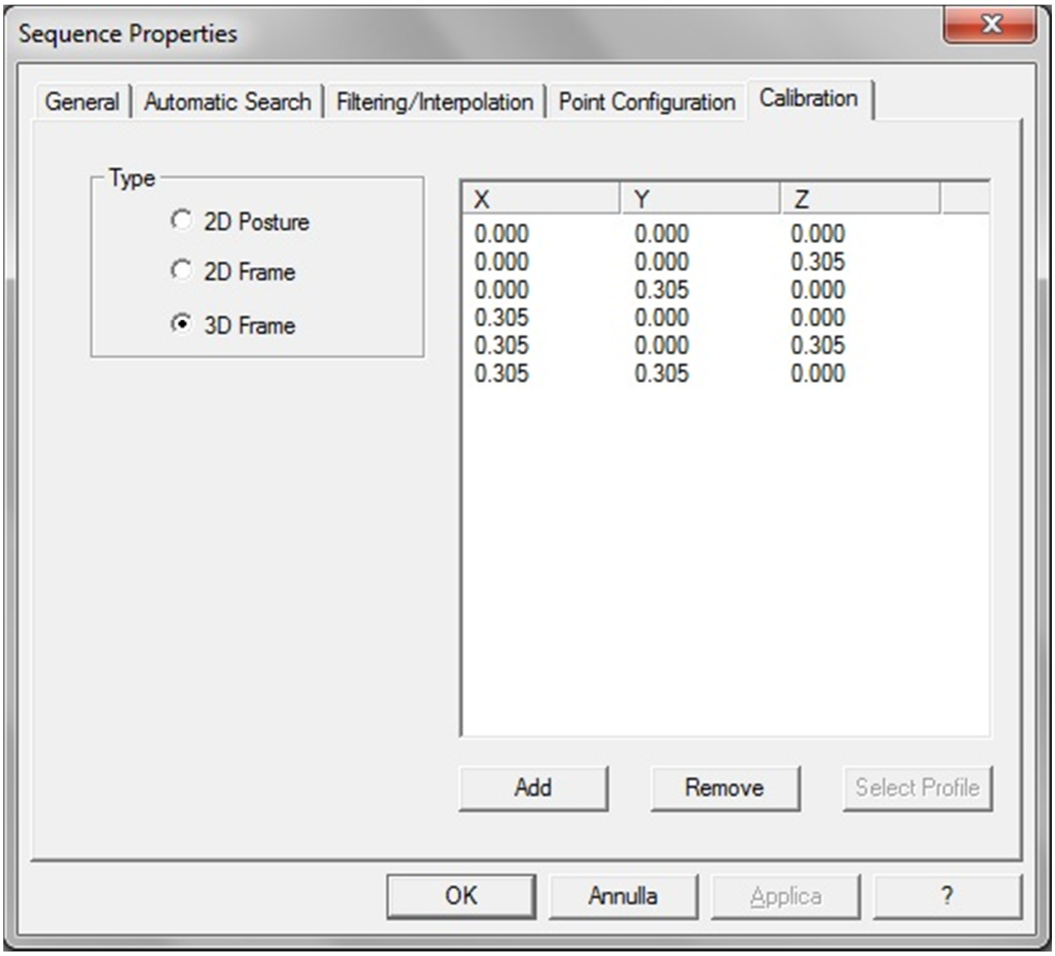


**Figure 10.** 3-D Calibration options window

However, the camera was often too close to the athletes at the moment of the impact and none of the ring posts was visible in the shot. In these cases, the procedure was a little longer.

We had to look into the whole footage for a frame in which one of the boxers was very close to the ropes or was entirely framed. This way we could make a proportion between the distance between the ropes, or the athlete's height, in centimeters and in pixels and find out the length of one relevant body part, for example the head or the back or the arm. Then we had to come back to the impact frames and find references of angles, such as the directions of the ropes, when visible, or of the advertising logos on the canvas. Finally with all this information about angles and lengths we had to estimate the angle values at the point we were using as the origin of the coordinates system and calculate the lengths of the segments in perspective. In instances like this, the resulting error can be assumed to be higher.

An example of the result can be seen in the next figure (Figure 11):


**Figure 11.** Calibration with the boxer's head as a reference

## 2.2.2 Actual motion tracking

After completing the calibration, we executed the actual motion tracking.

In SkillSpector, this is done by marking a certain number of significant points in each and every frame of the different cameras we selected previously. Several models (Full body, Simple Full Body, Right Leg, etc..) are provided by the software but none of them fitted our needs so we simply created a new one called "Head and Arm", made of eight points

(Shoulder, Elbow, Finger, Right Ear, Left Ear, Chin, Nose, Forehead) and one segment, which connected the ears and represented the head (Figure 12 and 13).

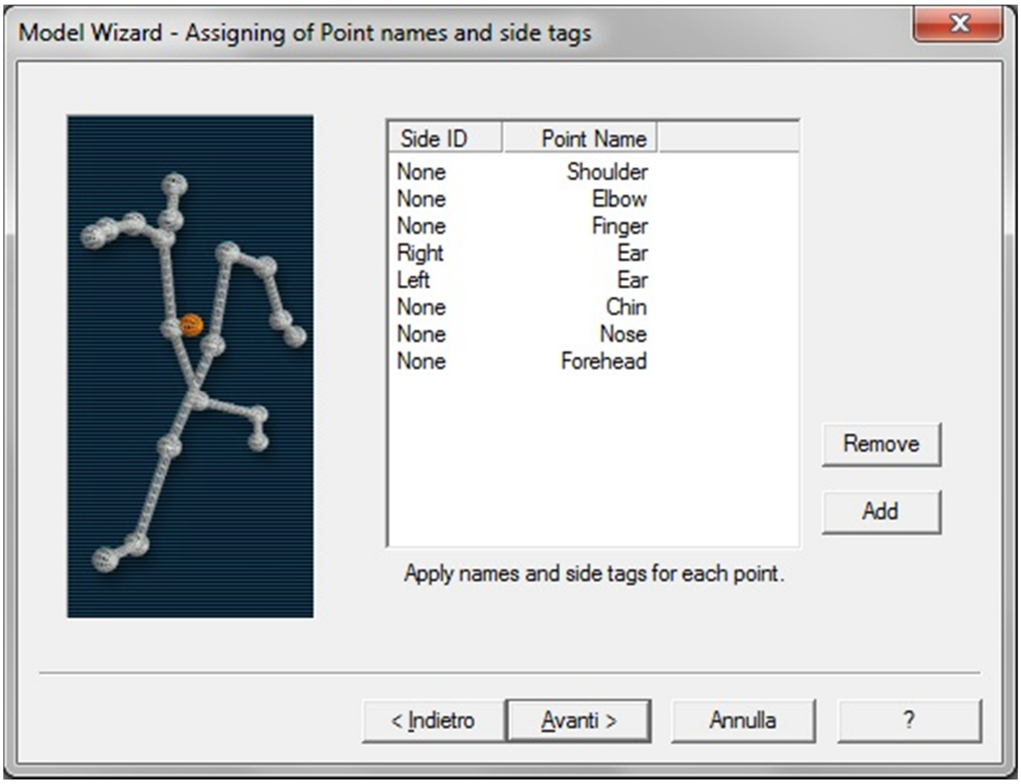


**Figure 12.** Model's points

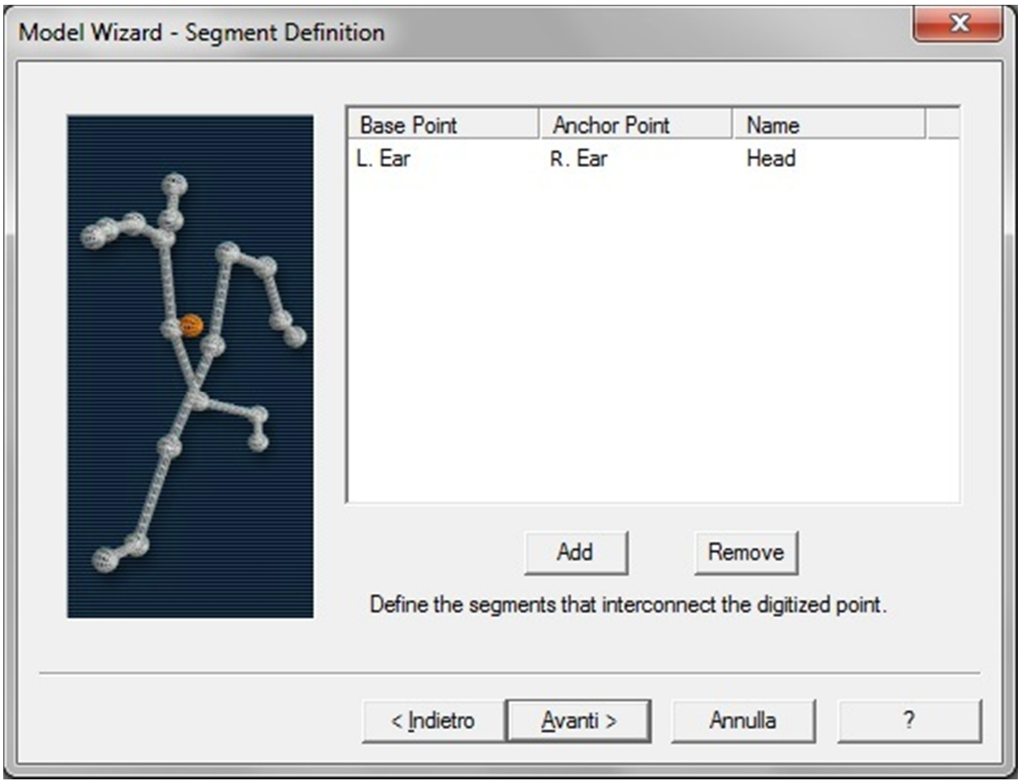


**Figure 13.** Model's segments

Here is an example of the points marked in a motion tracking using SkillSpector (Fig 14):

**Figure 14.** Points marking of one frame

## 2.2.3 Data analysis and results

At this point, SkillSpector could calculate all the data we were looking for (Figure 15) in this study:

- The hand translational velocity and acceleration.
- The head rotational velocity and acceleration.

- The head's center of gravity translational acceleration.

To calculate the CG translational acceleration we actually asked the software for the Left Ear and Right Ear linear accelerations. Then, considering the hypothesis of the head as a rigid body, we took the mean of these two values.

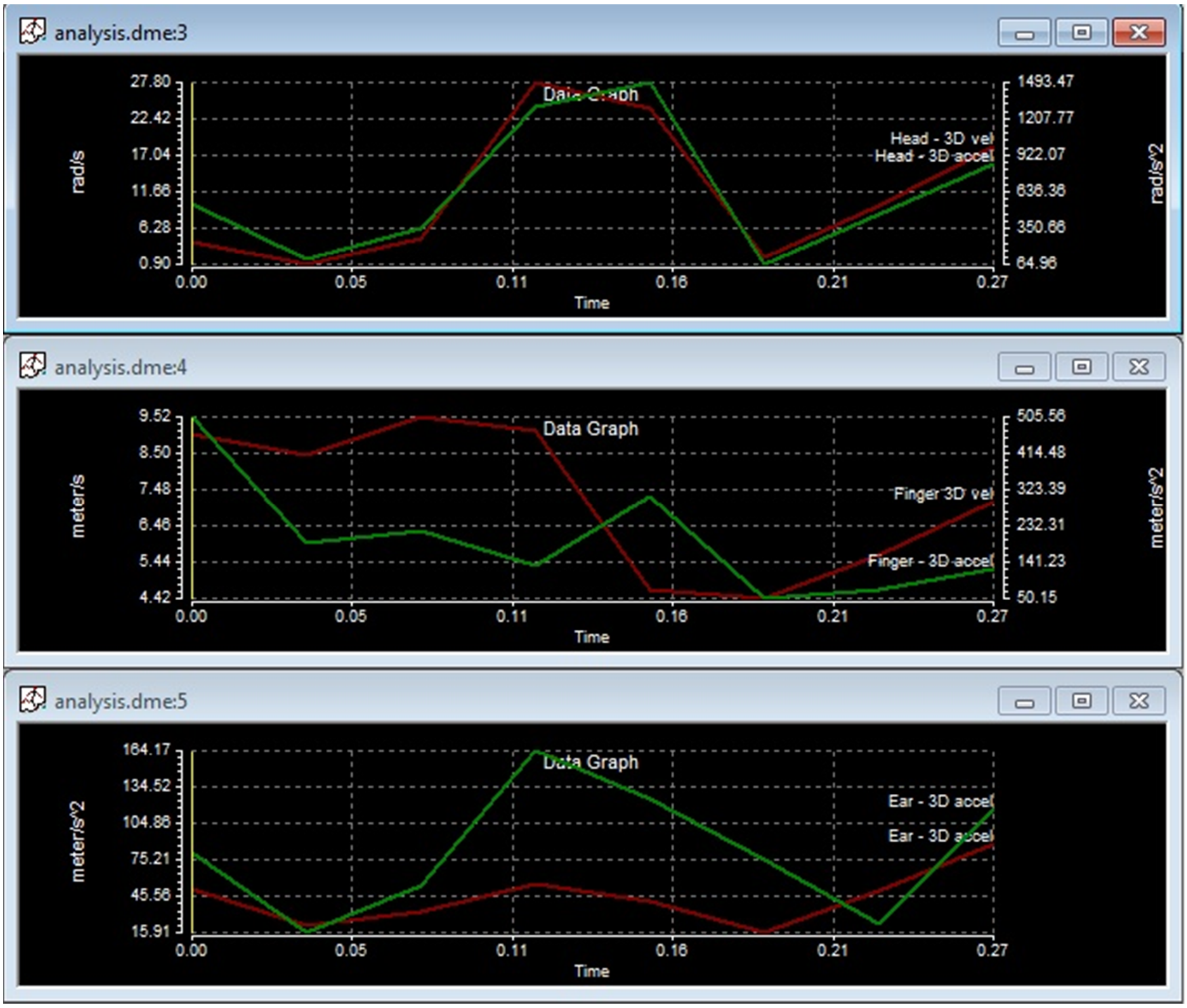


**Figure 15.** Graphs elaborated by SkillSpector

Looking at these graphs, it is clear that only three points (Finger, Left Ear, Right Ear) and the Head segment were sufficient to find all the results we were interested in. However, we decided to mark the other points that could serve for future studies, e.g. for an in-depth study of the movements of the attacker's arm or the head of the hit boxer.

# 3. MATLAB based data elaboration

The data collected with SkillSpector were raw and needed to be elaborated in order to make them more relevant for the final analysis.

This elaboration, achieved using MATLAB, included basically three phases that are described in detail later:

- An interpolation of the raw data, in which we applied spline curves to get smoothed graphs of the values, for example "head rotational acceleration vs time".
- A calculation of the Head Injury Criterion (HIC) value of each impact.
- A Student's t-test on the maximum values of head rotational acceleration divided in groups depending on the frame rate of the respective video.

First of all, in detail, the main MATLAB function myspline.m:

```
clear all;
close all;
clc;

%Input file and datas.
match=input('File name (without extension): \n','s');
datas=load([match,'.txt']);
fps=input('Number of frames per second of the video (2 decimal digits): \n');
check='a';
while ((check~='y')&&(check~='n'))
    check=input('Do you want to use all the frames? [y/n] \n','s');
    if (check=='y')
    s=1;
    e=length(datas(1,:));
    else
        if (check=='n')
            s=input('Starting frame \n');
            e=input('Ending frame \n');
        end;
    end;
end;
```

A set of .txt files containing the raw output data of the SkillSpector analysis of the boxing matches was previously created and used as input for this MATLAB function (line 16). In each and every file the first and the second rows were the values of the head rotational velocity and acceleration respectively. The third and the fourth rows were the values of the hand translational velocity and acceleration respectively. The fifth and the sixth were the translational accelerations of the ears. Another input needed was the fps value of the video (line 17).

Earlier in the analysis, during the video-editing part of the study, in some cases one or two more frames were kept at the beginning or at the end of the video even if they did not show movements of the head and the arm strictly related to the impact. Sometimes this led to unexpected high values visible at the beginning or at the end of the graphs (see Figure 14) in SkillSpector. In order to get reasonable results regarding the spline interpolation and the HIC value calculation, these values needed to be ignored. This is the reason why it is asked as input (lines 19 to 30) in this MATLAB function.

```
31      disp('Which graphs do you need? [1/2/3/4/5]');
32      disp('1 = Head Rotational Acceleration');
33      disp('2 = Head Rotational Velocity');
34      disp('3 = Hand Linear Acceleration ');
35      disp('4 = Hand Linear Velocity ');
36      fun=input('5 = Center of Gravity Linear Acceleration \n');
37      switch fun
38          case 1
39              m=head_a(match,datas,fps,s,e);
40              disp(['Maximum Head Rotational Acceleration value [ras/s^2] = ',...
41                  num2str(m(1))]);
42              %Realtive error in under-sampled head acceleration's splines.
43              err=(abs(m(1)-m))/m(1)*100;
44              err=err(2:length(err));
45              disp(['Under-sampled HRA splines relative error values (%) = ',...
46                  num2str(err)]);
47          case 2
48              head_v(match,datas,fps,s,e);
49          case 3
50              hand_a(match,datas,fps,s,e);
51          case 4
52              hand_v(match,datas,fps,s,e);
53          case 5
54              [sp,t]=CG_a(match,datas,fps,s,e);
55              % HIC calculation.
56              hic_val=HIC(sp,t,fps,match);
57              disp(['The HIC value is equal to ', num2str(hic_val)]);
58      end;
```

After that (lines 31 to 58), it is simply asked to the user which information he is interested in and, depending on that, many other MATLAB functions are called. Note that the calculation of the HIC value (line 56) is obviously subject to the analysis of the center of gravity linear acceleration.

## 3.1 Spline curves interpolation

The main “myspline.m” function calls five others: head_v, head_a, hand_v, hand_a, CG_a.

These perform the spline interpolation respectively for the data of head rotational velocity, acceleration, hand translational velocity, acceleration and center of gravity translational acceleration. All five of them are very similar in terms of the MATLAB code. Hence, we show only one, the one concerning the head rotational acceleration, below:

```
function m=head_a(match,datas,fps,s,e)

switch fps
    case 89.91
        m=head_a90(match,datas,s,e);
    case 75.00
        m=head_a75(match,datas,s,e);
    case 59.94
        m=head_a60(match,datas,s,e);
    case 49.95
        m=head_a50(match,datas,s,e);
    case 29.97
        m=head_a30(match,datas,s,e);
end;
```

The only purpose of this function is to check the value of the frame rate of the video and to use it to call the proper function which actually performs the spline interpolation and plots the results.

Also the functions called here are similar to one another, so only the first one of them, head_a90 (line 12), is hereby discussed:

```
8   function max_vect=head_a90(match,datas,s,e)
9
10  %Splines for acceleration.
11  max_vect1=[];
12  max_vect2=[];
13  fps=89.91;
14  h_a=datas(2,(s:e));
15  t_vect=[0:(1/fps):((length(h_a)-1)/fps)];
16  x1=[t_vect(1):t_vect(end)/100:t_vect(end)];
17  sp1=spline(t_vect,h_a,x1);
18
19  %Head rotational acceleration plot.
20  figure(1);
21  plot(t_vect,h_a,'o',x1,sp1);
22  title ('Head Rotational Acceleration: 90 fps Spline');
23  xlabel('Time [s]');
24  ylabel('Acceleration [rad/s^2]');
25  axis([t_vect(1) t_vect(end) ((min([min(sp1) min(h_a)]))-100)...
26      ((max([max(sp1) max(h_a)]))+100)]);
27
28  %Save figure.
29  saveas(1,[match,'1.bmp']);
```

In this first part of the function, the raw values are used to create a spline curve and to plot it. Firstly, the time vector is created (line 15) according to the frame rate of the video and is taken as the domain of the data. Then, with this one and the acceleration vector, the “spline” function is called (line 17) and sampled at many more points, 100 times more points (line 16), than the domain in order to get a smoother plot of it.

The function “spline” in MATLAB uses a cubic spline interpolation. The third degree polynomial is the one that is most typically chosen for constructing smooth curves in computer graphics. It is used because it is the lowest degree polynomial that can support an inflection, so realistic curves can be made. Furthermore it is very well behaved numerically, which means that the curve will usually be smooth and not jumpy. Another method that could have been used to perform a piecewise cubic interpolation is the MATLAB function “pchip”. We chose to use the spline function because it gave smoother results.

Here is an example of a plot (Figure 16) of the raw data (blue dots) collected with motion tracking and the resulting spline (green line):

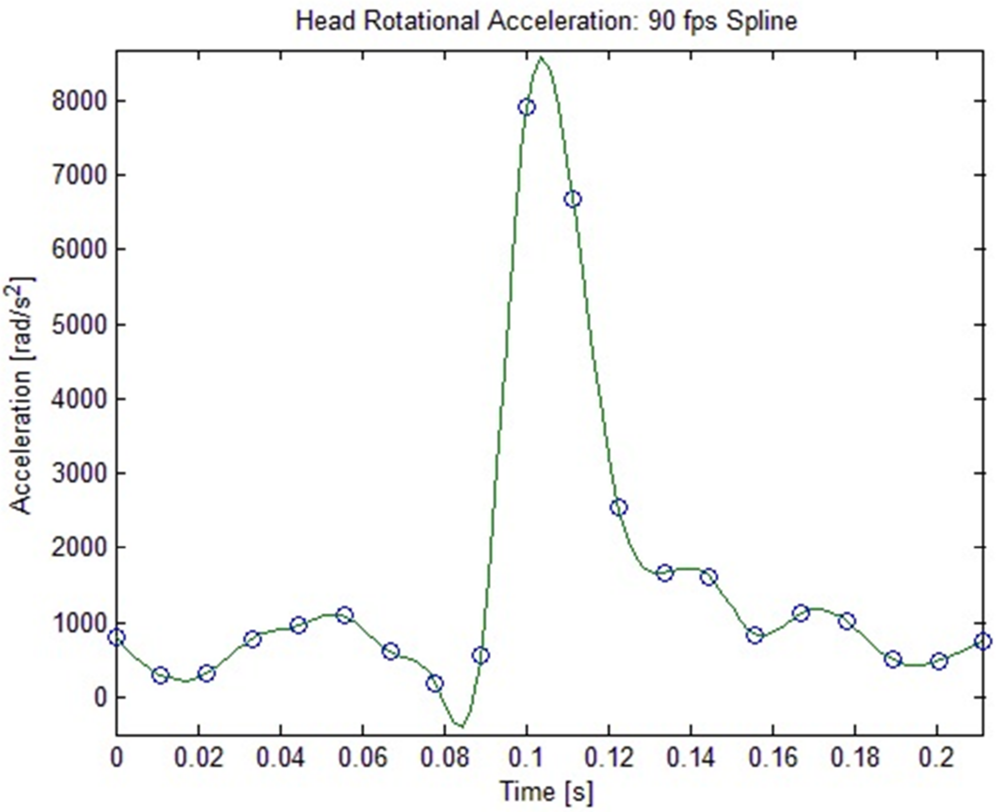


**Figure 16.** Example of three-dimensional head rotational acceleration's plot

A couple of things can be noticed in this plot:

- The maximum value of the spline is higher than the maximum value of the raw data. This happened in almost all cases studied.

- The spline gives us a good representation of the data but also has some drawbacks like the presence of some negative values which were never found among the raw data.

At this point, we wondered what would have happened if the data were collected with a lower frequency: would the resulting spline have had the same shape of the previous one or would it have been completely different?

Then in the second part of the function “head_a90” (see below) we decided to repeat the same procedure using just one out of three sampled values. This way it was possible to make a sort of comparison between these data and the ones relative to videos that have an actual frame rate of only a third (29.97 fps) of the one just shown.

```
%3 Splines at 30 fps.
figure(2);
subplot(221);
plot(t_vect,h_a,'o',x1,sp1);
xlabel('Time [s]');
ylabel('Acceleration [rad/s^2]');
title ('90 fps Spline');
axis([t_vect(1) t_vect(end) ((min([min(sp1) min(h_a)]))-100)...
    ((max([max(sp1) max(h_a)]))+100)]);
for k=1:3
    i=1;
    j=k;
    while (j<=length(h_a))
        h_a30(i)=h_a(j);
        t_vect30(i)=t_vect(j);
        i=i+1;
        j=j+3;
    end;
    x2=[t_vect30(1):t_vect30(end)/100:t_vect30(end)];
    sp30=spline(t_vect30,h_a30,x2);
    fig_index=221+k;
    subplot(fig_index);
    plot(t_vect30,h_a30,'o',x2,sp30);
    xlabel('Time [s]');
    ylabel('Acceleration [rad/s^2]');
    title (['Spline 30 fps n°' num2str(k)]);
    axis([t_vect(1) t_vect(end) ((min([min(sp1) min(sp30)]))-100)...
        ((max([max(sp1) max(sp30)]))+100)]);
    max_vect1=[max_vect1 max(sp30)];
    h_a30=[];
    t_vect30=[];
end;
max_vect1=mean(max_vect1);
```

The raw values were divided into three groups (lines 40 to 42) taking every three of either the first, the second or the third sample, respectively. Consequently also three time-domain vectors were created (line 45).

Doing this, it was possible to get three different splines (lines 50 to 58) by a “30-fps under-sampling”, out of each 90-fps video, and to compare their plots (Figure 17). Also this time the splines were sampled on a domain that was 100 times larger in order to make the plot smoother.

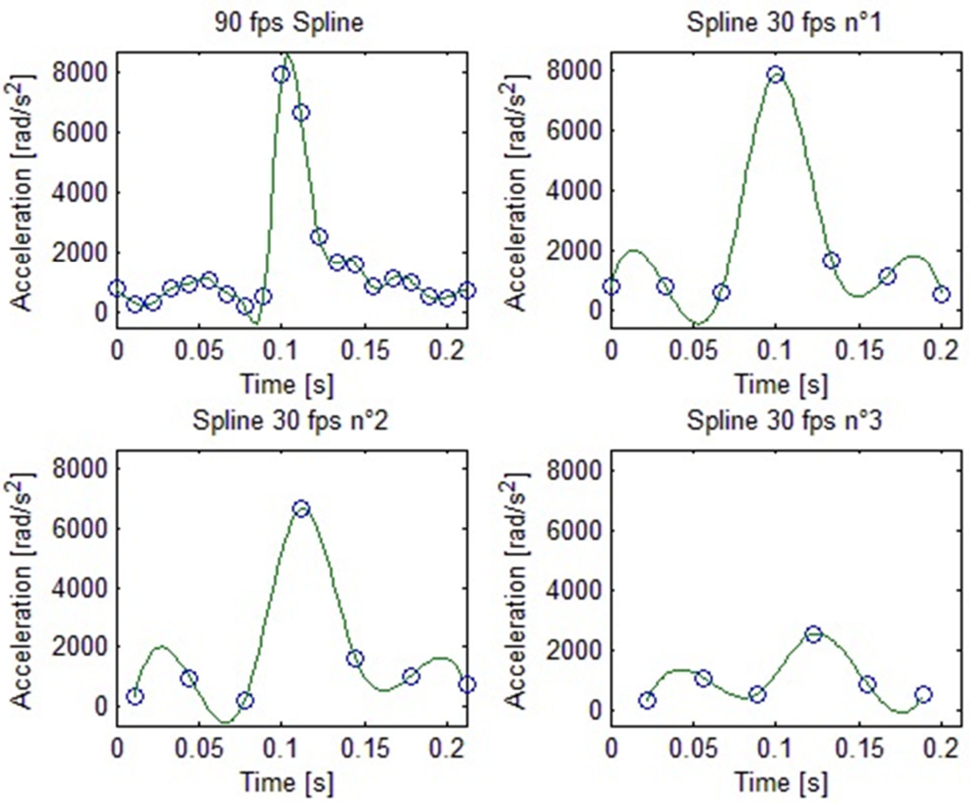


**Figure 17.** Comparative plot between a 90-fps spline and the three under-sampled 30-fps splines

The difference between the magnitude of the maximum value and the difference between the shapes of the four spline curves are immediately noticeable. The peak of head rotational acceleration is usually enclosed in a time lapse of about three frames at an 89.91 fps frequency, which means that by under-sampling at one third of the frequency the results can vary a lot. They could be quite similar to the original ones, like in the first example, or they could be extremely different. In the third example, it is clear how the peak is difficult to recognize and its maximum value is less than a half of the original one. We tried to estimate the magnitude of this difference by taking note of the maximum values of the different splines and doing an average (line 63) of them. Subsequently the relative percentage “error” of the under-sampling procedure was calculated (myspline.m, lines 43 to 46).

In the last part of this MATLAB function, we also perform an under-sampling at 45 (44.955, precisely) fps to have a better understanding of the relation between the spline curves and the sample frequency. This time we got obviously only two different splines (one frame taken every two of them) but, since the code is very similar to the previous one, it is not shown here. Just an example of plot is reported (Figure 18):

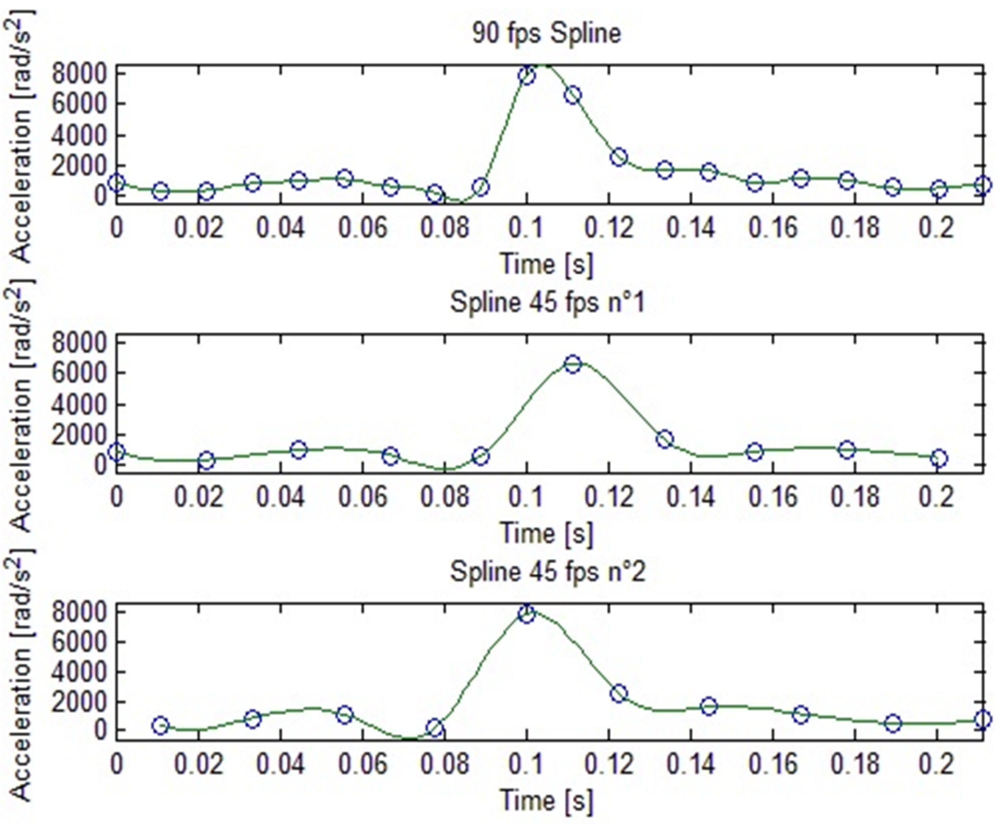


**Figure 18.** Comparative plot between a 90-fps spline and the two under-sampled 45-fps splines

On the other videos, with different original frame rates, the same procedure was executed by other MATLAB functions, in particular:

- head_a75; the original frame rate was 75.00 so three different splines under-sampled at 25.00 fps were obtained.
- head_a60; the original frame rate was 59.94 so two different splines under-sampled at 29.97 fps were obtained.
- head_a50; the original frame rate was 49.95 so two different splines under-sampled at almost 25 fps were obtained.
- head_a30; the original frame rate was 29.97 so this time we did the opposite and tried to over-sample the original spline with a frequency equal to the triple, i.e. 89.91 fps, to see if the result was significantly different. One example of this is show below (Figure 19):

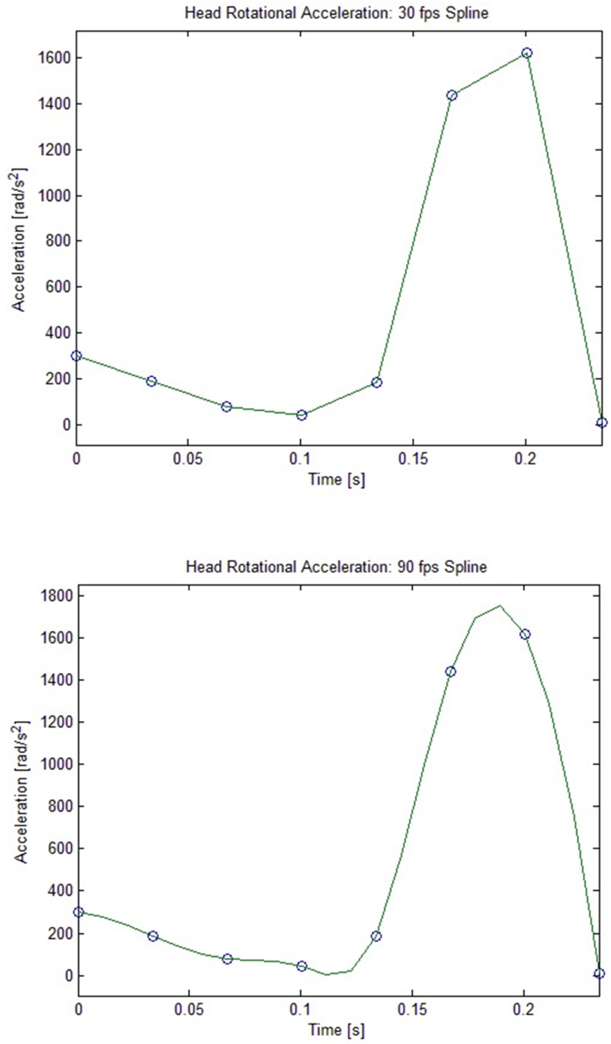


**Figure 19.** Comparative plot between a 30-fps spline and the relative over-sampled 90-fps spline

# 3.2 HIC (Head Injury Criterion) value

In the event of an impact to the head, the peak in head angular motion is the value most correlated with the damage suffered [27]. However, another index frequently taken into consideration to evaluate a hit, mostly in experiments to assess safety related to vehicles, is the Head Injury Criterion.

The HIC score is based on the three-dimensional translational acceleration of the center of gravity of the head. It does not have any specific meaning in terms of injury mechanism and actually is not an injury predictor but just a pass/fail baseline measure.

It was initially defined as:

$$HIC = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a\,dt \right]^{2.5} (t_2 - t_1)$$

Where

a is a resultant head acceleration

$t_2 - t_1 \leq 36$ ms

$t_2$, $t_1$ selected so as to maximize HIC

However, in 2000, the U.S. NHTSA (National Highway Traffic Safety Administration) prescribed to reduce the maximum time for calculating the HIC to 15 milliseconds [18].

Just to make few examples, at a HIC value equal to 1000, one out of six people will suffer a life-threatening injury to the brain. More specifically she will have 18% probability of a severe head injury, a 55% probability of a serious injury and a 90% probability of a moderate head injury to the average adult [19]. The previously quoted paper by Viano, published in 2003, based on the reconstruction of impacts happened during American football matches and on the study of straight punches thrown by Olympic boxers to a dummy, set the nominal tolerance for concussion at a HIC score equal to 250. In the study, however, the role of the rotational acceleration in concussion was unclear so we have to be cautious with this value.

In order to calculate the HIC value in the studied impacts, it was then essential to get to know the translational acceleration of the center of gravity of the head. Since it was not possible to track the movements of the CG, we simply took into consideration the acceleration of the left ear and the right ear. Under the hypothesis of the human head as a rigid body and knowing that the CG is located on a plane at the same distance between the ears, we calculated the average of their linear acceleration and used this value as an estimation of the CG translational acceleration.

Finally we performed the spline interpolation of that and gave the result as an input to the MATLAB function “HIC.m”, which is shown below:

```
function max_val=HIC(sp,t,fps,match)
if fps==29.97
    freq=3*fps;
else
    freq=100;
end;
ihic0=0;
ihic1=0;
max_val=0;
integ=zeros(length(t));
integ(1)=0.0;
%calculate the integral.
for i=2:length(t)
    integ(i)=integ(i-1)+(sp(i)+sp(i-1))/2;
end;
%Find the max value.
for i=1:length(t)-1
    for j=1:length(t)
        if (((j-i)/freq)<0.015)
            val=(integ(j)-integ(i))/(j-i);
            if(val>0.0)
                val=val^2.5;
            else
                val=0;
            end;
            val=val*(j-i)/freq;
            if (val>max_val)
                max_val=val;
                ihic0=i;
                ihic1=j;
            end;
        end;
    end;
end;
```

As can be seen the integral was calculated numerically using the trapezoidal rule (line 20) and, after that, it was checked which was the time interval that maximize the HIC value (lines 23 to 40).

The final part of the function, not reported here, plotted the spline interpolation curve of the CG translational acceleration highlighting the interval where the HIC score was calculated (Figure 20).

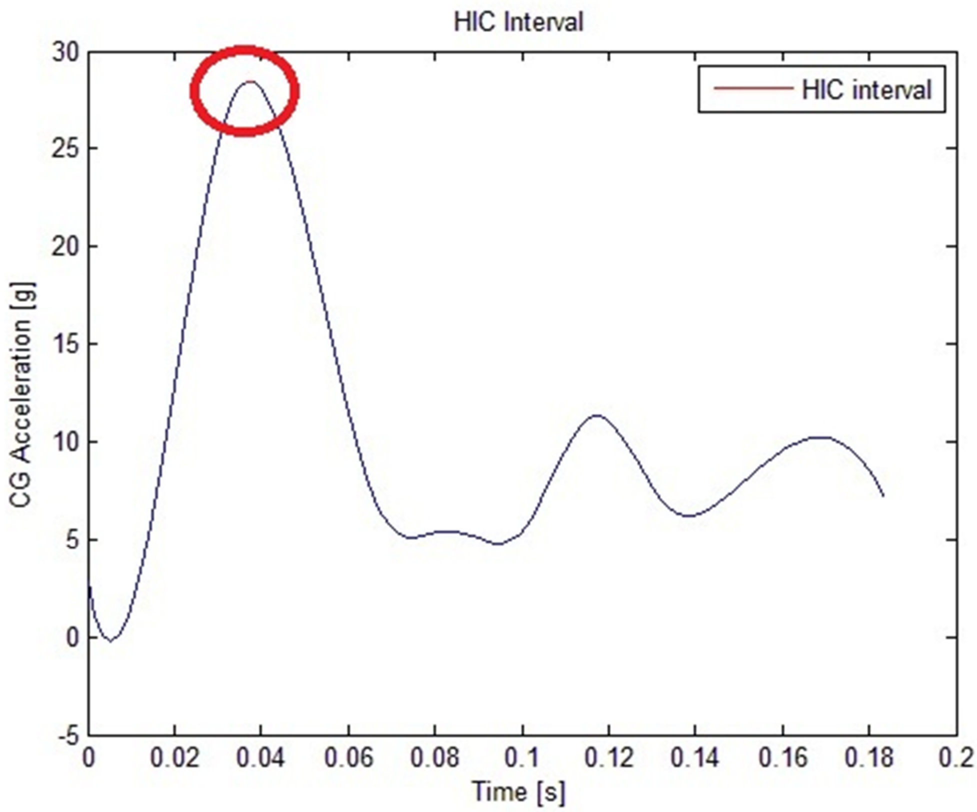


**Figure 20.** CG translational acceleration and HIC interval

Looking at the figure above, which is similar to the respective figures of CG linear acceleration obtained in many other cases, it is clear that usually impacts in boxing are longer than impacts in car accident. Then maybe a larger maximum time interval should be used in the formula to calculate the Head Injury Criterion.

# 3.3 Wilcoxon rank-sum test

The data elaboration part of this study ended with a statistical test on the values that were most relevant to us, i.e. the peak values of the head rotational acceleration. As previously said, in this analysis we worked on several videos with different frame rates which led to differences in the results. We were interested in knowing whether these differences were statistically significant, hence we wanted to verify the null hypothesis that the values were independent random samples from normal distributions with equal means and equal but unknown variances, against the alternative that the means were not equal.

In order to execute this verification we wrote another MATLAB function called “r_sum_test.m” which is shown below:

```
%Load data file.
load Stats.txt
a=Stats(:,2);

%KOs groups (30-60-90 fps).
gr1=a(1:6);
gr2=a(9:15);
gr3=a(18:25);

%Wilcoxon tests
[p12,h12] = ranksum(gr1,gr2);
disp('Rank-sum test between KOs HRA max values at 30 and 60 fps (5% significance level):');
if (h12==0)
    disp('Failure to reject the null hypotesis');
else
    disp('Null hypotesis rejected');
end;
disp(['The p-value is equal to ', num2str(p12)]);

[p23,h23] = ranksum(gr2,gr3);
disp('Rank-sum test between KOs HRA max values at 60 and 90 fps (5% significance level):');
if (h23==0)
    disp('Failure to reject the null hypotesis');
else
    disp('Null hypotesis rejected');
end;
disp(['The p-value is equal to ', num2str(p23)]);
```

Firstly, a file (Stats.txt) containing two columns of data, fps and peak values of the head rotational acceleration was loaded (line 9). Then the Wilcoxon rank-sum test was performed simply calling the function “ranksum” (line 18) already present in MATLAB. This function produced a value equal to 1 when the null hypothesis was rejected at the 5% of significance level and equal to 0 when a failure to reject such hypothesis happened. We also got as an output the p-value to see explicitly if the null hypothesis was rejected or could not be rejected at that significance level.

The test was performed only between the groups of values related to the KOs matches at “30 and 60” and “60 and 90” frames per second and to the Other Hits matches at “30 and 60” fps. This choice was made because there were too few cases in the other groups to be statistically significant.

In the last part of the function, the values of the acceleration used in the Wilcoxon rank-sum test were plotted.

# 4. Discussion and results

The results obtained in this study are reported below. Firstly, the raw data from the motion tracking of each KO (Table 6) and Other Hits video (Table 7):

| Match Number | Video FPS | Head | | | Hand | |
|---|---|---|---|---|---|---|
| | | Rotational Velocity [rad/s] | Rotational Acceleration [rad/s$^2$] | CG Linear Acceleration [g] | Linear Velociy [m/s] | Linear Acceleration [g] |
| 1 | 29,97 | 29,89 | 1618,75 | 6,83 | 7,92 | 13,69 |
| 2 | 29,97 | 52,84 | 4122,00 | 10,13 | 16,30 | 91,80 |
| 3 | 29,97 | 29,60 | 1367,60 | 11,43 | 8,98 | 23,82 |
| 4 | 29,97 | 27,80 | 1493,47 | 11,25 | 9,52 | 31,19 |
| 5 | 29,97 | 27,82 | 1224,29 | 8,41 | 18,48 | 39,83 |
| 6 | 29,97 | 26,72 | 5846,25 | 14,07 | 13,20 | 34,77 |
| 7 | 49,95 | 65,05 | 4776,38 | 19,48 | 9,16 | 102,39 |
| 8 | 49,95 | 76,40 | 7594,72 | 26,99 | 11,79 | 63,58 |
| 9 | 59,94 | 59,99 | 4891,86 | 19,73 | 5,22 | 27,72 |
| 10 | 59,94 | 38,74 | 3841,56 | 19,34 | 9,39 | 44,27 |
| 11 | 59,94 | 43,51 | 7590,00 | 34,91 | 11,81 | 132,16 |
| 12 | 59,94 | 44,14 | 6806,32 | 20,94 | 13,69 | 65,02 |
| 13 | 59,94 | 27,26 | 3380,24 | 18,69 | 6,30 | 26,07 |
| 14 | 59,94 | 19,92 | 4225,38 | 38,63 | 13,09 | 82,58 |
| 15 | 59,94 | 25,67 | 4368,69 | 42,59 | 21,43 | 64,97 |
| 16 | 75,00 | 130,41 | 14275,54 | 29,95 | 14,36 | 53,86 |
| 17 | 75,00 | 39,20 | 7855,31 | 37,12 | 13,57 | 64,60 |
| 18 | 89,91 | 64,15 | 5185,15 | 46,14 | 13,65 | 68,34 |
| 19 | 89,91 | 33,65 | 8218,19 | 64,25 | 28,78 | 202,78 |
| 20 | 89,91 | 88,06 | 9018,18 | 52,43 | 19,82 | 77,40 |
| 21 | 89,91 | 71,24 | 13081,58 | 43,62 | 14,07 | 95,41 |
| 22 | 89,91 | 62,72 | 6504,89 | 40,29 | 24,75 | 96,58 |
| 23 | 89,91 | 43,10 | 7896,53 | 33,47 | 16,45 | 93,21 |
| 24 | 89,91 | 83,16 | 8894,00 | 46,07 | 8,89 | 69,46 |
| 25 | 89,91 | 56,63 | 7067,91 | 51,53 | 14,02 | 114,09 |

**Table6.** Raw data of the KO videos

| Match Number | Video FPS | Head | | | Hand | |
|---|---|---|---|---|---|---|
| | | Rotational Velociy [rad/s] | Rotational Acceleration [rad/s²] | CG Linear Acceleration [g] | Linear Velociy [m/s] | Linear Acceleration [g] |
| 1 | 29,97 | 36,958 | 2786,263 | 28,601 | 13,399 | 28,001 |
| 2 | 29,97 | 32,931 | 1310,414 | 6,885 | 10,959 | 43,334 |
| 3 | 29,97 | 22,105 | 862,091 | 4,164 | 11,445 | 38,323 |
| 4 | 29,97 | 52,114 | 2741,361 | 19,549 | 46,834 | 136,159 |
| 5 | 29,97 | 13,638 | 678,374 | 7,544 | 12,582 | 38,789 |
| 6 | 59,94 | 27,264 | 2643,800 | 15,562 | 12,506 | 42,364 |
| 7 | 59,94 | 5,599 | 768,519 | 18,408 | 19,754 | 81,681 |
| 8 | 59,94 | 38,552 | 5351,336 | 24,991 | 10,268 | 67,460 |
| 9 | 59,94 | 55,748 | 4953,597 | 38,627 | 13,304 | 65,305 |
| 10 | 89,91 | 24,931 | 3906,683 | 26,751 | 15,685 | 91,507 |

**Table 7.** Raw data of the Other Hits videos

The data above are to be intended as the maximum values during the movements of the arm and the head following the impact.

Table 8 and Table 9 below show the mean values and the standard deviations of the previous data. The different groups are divided according to the frame rate value:

| Group Number | Video FPS | Head | | | Hand | |
|---|---|---|---|---|---|---|
| | | Rotational Velociy [rad/s] | Rotational Acceleration [rad/s²] | CG Linear Acceleration [g] | Linear Velociy [m/s] | Linear Acceleration [g] |
| 1 | 29,97 | 32,44 (10,06) | 2612,03 (1921,06) | 10,35 (2,53) | 12,40 (4,31) | 39,18 (27,35) |
| 2 | 49,95 | 70,72 (8,03) | 6185,55 (1992,87) | 23,24 (5,31) | 10,47 (1,86) | 82,99 (27,44) |
| 3 | 59,94 | 37,03 (13,78) | 5014,86 (1578,25) | 27,83 (10,44) | 11,56 (5,43) | 63,25 (36,82) |
| 4 | 75,00 | 84,80 (64,49) | 11065,42 (4539,79) | 33,54 (5,07) | 13,96 (0,56) | 59,23 (7,60) |
| 5 | 89,81 | 62,84 (18,52) | 8233,30 (2339,38) | 47,23 (9,17) | 17,55 (6,54) | 102,16 (43,51) |

**Table 8.** Mean values (SD) of the peaks in KO videos

| Group Number | Video FPS | Head | | | Hand | |
|---|---|---|---|---|---|---|
| | | Rotational Velociy [rad/s] | Rotational Acceleration [rad/s$^2$] | CG Linear Acceleration [g] | Linear Velociy [m/s] | Linear Acceleration [g] |
| 1 | 29,97 | 31,55 (14,70) | 1675,70 (1019,69) | 13,35 (10,38) | 19,04 (15,56) | 56,92 (44,65) |
| 2 | 59,94 | 31,79 (21,02) | 3429,31 (2138,10) | 24,40 (10,28) | 13,96 (4,07) | 64,20 (16,27) |
| 3 | 89,91 | 24,931 | 3906,683 | 26,751 | 15,685 | 91,507 |

**Table 9.** Mean values (SD) of the peaks in Other Hits videos

Finally, the elaborated data of each case (Table 10 and 11) are presented to show the maximum values of the spline curves interpolating the head angular acceleration, the percentage difference between the maximum of the under-sampled (over-sampled, when the original fps is equal to 29.97) splines and the original one, the HIC value.

| Match Number | Video FPS | Peak value of the original spline [rad/s$^2$] | Percentage difference in the other splines* [%] | HIC value |
|---|---|---|---|---|
| 1 | 29,97 | 1752,82 | 7,65 | 5,34 |
| 2 | 29,97 | 4314,42 | 4,47 | 7,11 |
| 3 | 29,97 | 1672,49 | 18,22 | 6,97 |
| 4 | 29,97 | 1581,23 | 5,55 | 0,87 |
| 5 | 29,97 | 1224,28 | 0,00 | 8,22 |
| 6 | 29,97 | 6182,23 | 3,48 | 8,39 |
| **Mean** | **29,97** | **2787,91** | **6,56** | **6,15** |
| **SD** | | **2003,41** | **6,25** | **2,81** |
| 7 | 49,95 | 4812,38 | 12,54 | 21,57 |
| 8 | 49,95 | 7859,82 | 13,55 | 96,82 |
| **Mean** | **49,95** | **6336,10** | **13,05** | **59,19** |
| **SD** | | **2154,86** | **0,71** | **53,21** |
| 9 | 59,94 | 4976,75 | 2,37 | 54,56 |
| 10 | 59,94 | 3999,54 | 9,81 | 43,06 |
| 11 | 59,94 | 7800,81 | 20,05 | 115,19 |

| | | | | |
|---|---|---|---|---|
| 12 | 59,94 | 6961,73 | 13,11 | 58,33 |
| 13 | 59,94 | 3499,30 | 12,14 | 25,73 |
| 14 | 59,94 | 4401,31 | 9,66 | 28,12 |
| 15 | 59,94 | 4407,57 | 9,17 | 110,69 |
| **Mean** | **59,94** | **5149,57** | **10,90** | **62,24** |
| **SD** | | **1607,24** | **5,30** | **36,72** |
| 16 | 75,00 | 15345,57 | 25,12 | 77,59 |
| 17 | 75,00 | 8217,48 | 36,89 | 82,37 |
| **Mean** | **75,00** | **11781,52** | **31,01** | **79,98** |
| **SD** | | **5040,32** | **8,32** | **3,38** |
| 18 | 89,91 | 6818,96 | 15,05<br>46,14 | 363,61 |
| 19 | 89,91 | 8237,61 | 25,97<br>16,08 | 967,37 |
| 20 | 89,91 | 9631,96 | 21,70<br>6,54 | 187,85 |
| 21 | 89,91 | 13862,12 | 26,47<br>9,59 | 211,46 |
| 22 | 89,91 | 7066,06 | 21,92<br>9,14 | 178,11 |
| 23 | 89,91 | 8570,27 | 33,28<br>14,60 | 62,66 |
| 24 | 89,91 | 9015,95 | 26,21<br>7,38 | 108,62 |
| 25 | 89,91 | 7061,01 | 32,39<br>16,21 | 348,35 |
| **Mean** | **89,91** | **8782,99** | **25,37**<br>**15,71** | **303,50** |
| **SD** | | **2289,29** | **5,93**<br>**12,88** | **287,82** |

**Table 9.** Final data of KO videos
(* 1st group, spline at 90 fps; 2nd group, splines at 25 fps; 3rd group, splines at 30 fps; 4th group, splines at 25 fps; 5th group, spline at 30 and 45 fps)

| Match Number | Video FPS | Peak value of the original spline [rad/s$^2$] | Percentage difference in the other splines* [%] | HIC value |
|---|---|---|---|---|
| 1 | 29,97 | 3022,97 | 7,83 | 3,87 |
| 2 | 29,97 | 1517,52 | 2,25 | 0,85 |
| 3 | 29,97 | 862,09 | 0,00 | 0,78 |
| 4 | 29,97 | 3057,23 | 10,33 | 15,42 |
| 5 | 29,97 | 686,92 | 1,24 | 0,65 |
| **Mean** | **29,97** | **1829,35** | **4,33** | **4,31** |
| **SD** | | **1147,87** | **4,50** | **6,35** |
| 6 | 59,94 | 2915,75 | 11,34 | 4,59 |
| 7 | 59,94 | 770,43 | 11,34 | 34,06 |
| 8 | 59,94 | 5351,34 | 14,03 | 27,25 |
| 9 | 59,94 | 5453,22 | 6,76 | 6,76 |
| **Mean** | **59,94** | **3622,68** | **10,87** | **18,16** |
| **SD** | | **2234,15** | **3,02** | **14,72** |
| 10 | **89,91** | **3921,04** | **9,88**<br>**1,90** | **51,26** |

**Table 10.** Final data of Other Hits videos

## 4.1 Relation between frame rate and maximum values

Looking at the tables above, it is evident how almost all the data are strongly related to the frame rate of the videos, even if there are relevant differences between the KOs and the Other Hits. The reason why this is the case is that, as mentioned earlier, with a low value of fps, it is generally impossible to detect the peaks in the measured quantities such as rotational acceleration and velocity (see Figure 17). This leads to very distorted results.

Regarding the peaks in the head rotational acceleration, which is the most important measurement to us, we performed a Wilcoxon rank-sum test to check if this dependence on the frame rate was statistically relevant. At the 5% significance level, taking the knockouts into consideration (see Figure 21), the result was:

- A failure to reject, even if slightly, the null hypotesis comparing cases at 30 and 60 fps (p value = 0,051).
- A rejection of the null hypotesis between 60 and 90 fps (p value = 0,0037).

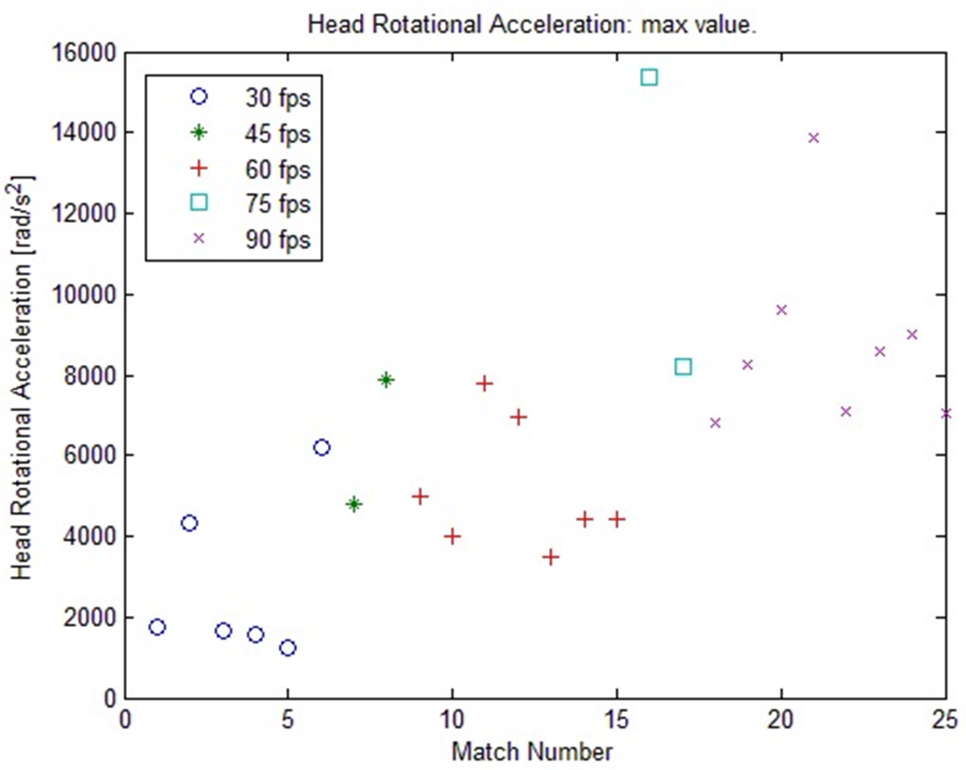


**Figure 21.** Peak values of head rotational acceleration spline curves of KO hits

This could be explained if we suppose that there is a threshold in the angular acceleration which determines whether a punch results in a concussion or not. In that case, all the KO hit values would obviously be above this threshold but it is realistic to think that most of them would not be too muchabove the limit. It would also be realistic for these values to be similar with one another, which means a dependence on the frame rate would be clearly visible.

Regarding, instead, the result of the Wilcoxon rank-sum test for the other major hits not resulting in knockouts (see Figure 22), at the 5% significance level, the result was a failure to reject the null hypotesis (p value = 0,41).

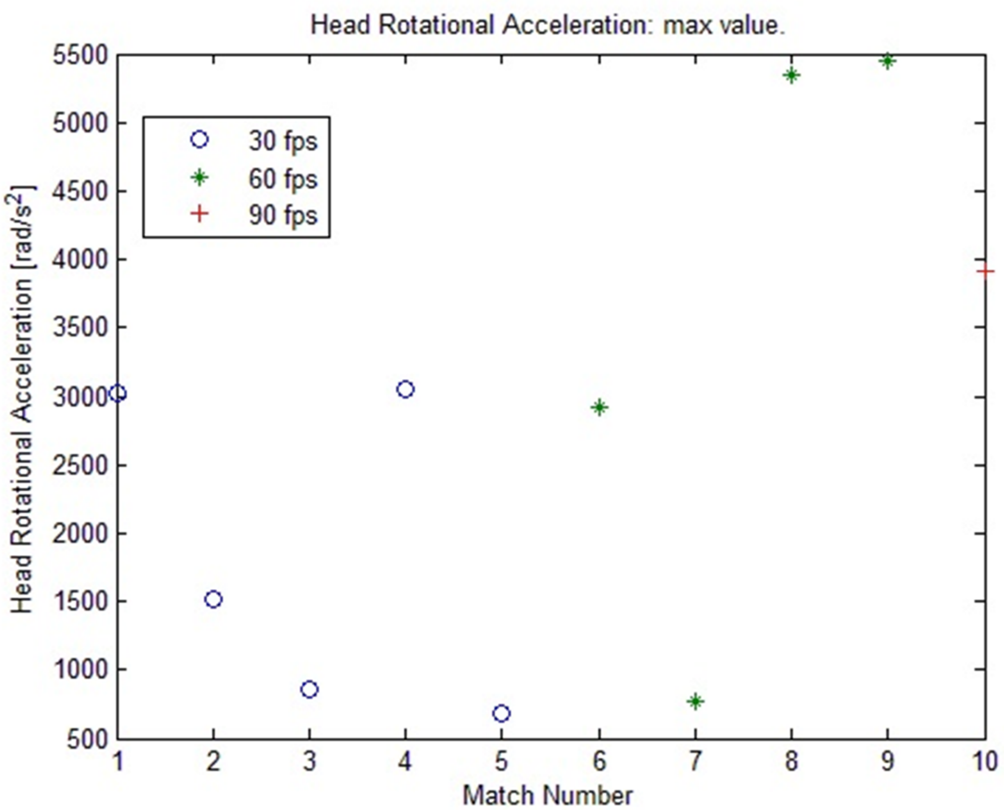


**Figure 22.** Peak values of head rotational acceleration spline curves of Other Hits

The maximum values of the Other Hits, in fact, could be not too significant because, when a concussion does not occur, the value is under a certain threshold. However, we cannot know how much close it is to that threshold.

For example, in Figure 22, the second data point is lower than the sixth one. This could be due to the bad sampling frequency but it could also be due simply to the fact that it corresponds to a weaker punch.

Following is a diagram representing the averages of the peak values, with standard deviation, of the head rotational acceleration in the different groups of impacts (Figure 23):

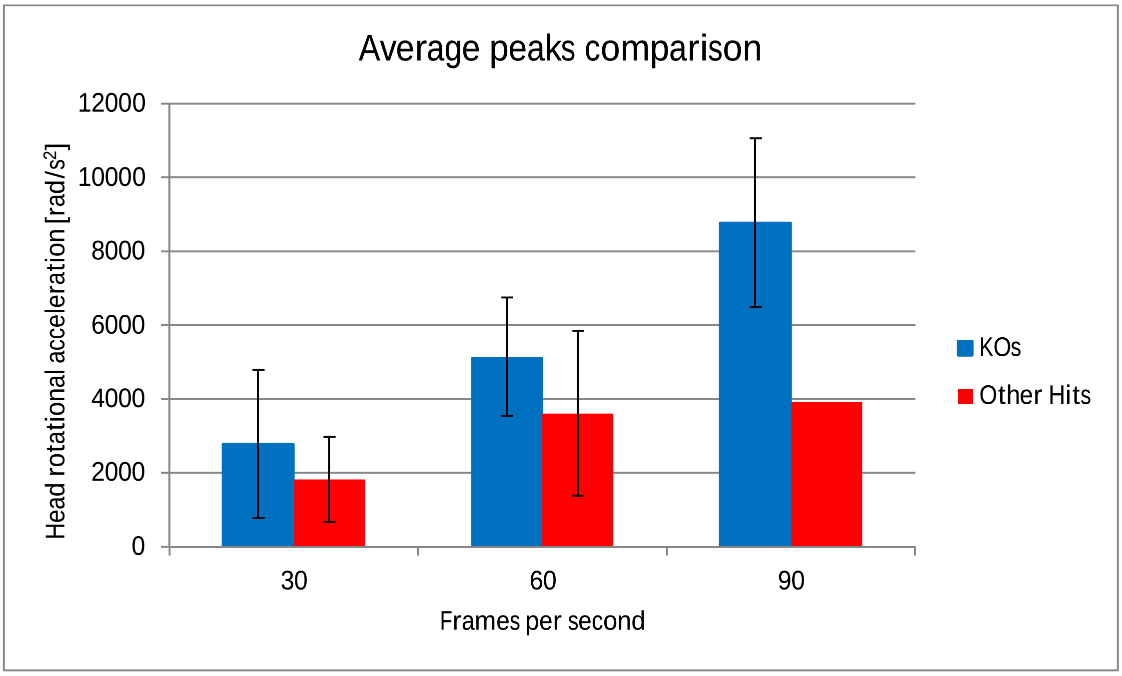


**Figure 23.** Average peaks of head rotational acceleration for the different group of cases

## 4.2 Comparison with data from previous studies

In the first chapter of this paper some previous studies, found in the literature, about head impacts and concussions were reported. Now, if we compare their results with the ones we got, it is possible to estimate how accurate motion tracking, based only on video analysis, is as a method to study the kinematics of a sports-related head trauma.

It is evident that from videos at 30, 50 and even 60 frames per second, we obtained too low values because of the under-sampling. Therefore these data are not comparable with the results from other studies. Values from the two videos at 75 fps are inexplicably high. However, since they are only two, we can discard them as not statistically relevant. For this reason, we took into consideration only the videos with a sampling frequency equal to 90 frames per second in our comparison.

We found that the average maximum value of the head rotational acceleration (8233±2339 rad/$s^2$) is larger then the one (7354±2897 rad/$s^2$) obtained by Zhang et al. in their study [20], previously quoted, about MTBIs in American football. Yet we can say that this is consistent with the threshold for concussions delineated in the same paper (see Table 3 and Figure 5) since it corresponds to a probability of more than 80% to suffer a mild traumatic brain injury. The same is for the HIC value, equal to 303.5, above the 80% of concussion probability in the study just quoted and also above the threshold for concussions, equal to 250, stated in the paper by Pellman et al. [23] (see Chapter 1).

The other magnitudes, velocity and accelerations, are almost comparable with the ones reported in the literature, taking into consideration impacts with the same head rotational acceleration and HIC, although we can see that the largest differences are in the linear values. This could be due to the difficulty in finding good references to evaluate the length of the segments than in finding good references for the angles between the axis during the calibration. It may also be due to the fact that the cameras recording the videos were not steady (see Chapter 2).

## 4.3 Causes of error

During the description of this motion tracking procedure many different causes of error were mentioned. All of them are related to the cameras used to record the boxing matches.

The main parameter to be evaluated in order to have good results is the frame rate of the cameras. In terms of head rotational acceleration, we noticed a direct dependence of the data on it (see Figure 23), with differences between peak values at 90 fps and the respective under-sampled at 30 fps larger than 50% in many cases.

Another major factor to be considered is that the cameras are not steady in order to follow the boxers on the ring. This means that, even in a small time lapse like the ones we are interested in, during our motion tracking, the camera, and therefore the origin of our coordinates system set in the calibration part of the video analysis, moves. Such a relative movement should be "subtracted" from the final values to get the data concerning the absolute movement of the boxers.

The relative movement of the axis' origin is not the only problem of the calibration we made. Actually the most relevant one is the lack, in many videos, of accurate references needed to set the axes' angles and the length of segments which compose our calibrating object. That forces us to have just an estimation of the correct coordinates system.

Finally, the last problem faced during the motion tracking of impacts occurred in matches dating back to the eighties was the low resolution of the cameras. Sometimes, marking the eight points of our model, it was difficult to recognize the different parts of the human head and this certainly led to inaccuracy in the determination of the positions which are used by the software to calculate all the other magnitudes.

## 4.4 Suggestions

As seen above, many possible causes of error can affect this method. Video-analysis based motion tracking could therefore be improved with some precautions.

First of all, using old footages like most of the ones in our database, the process of deinterlacing them, obviously if they were not recorded progressively, could double the value of the frame rate. This would be a great benefit in the detection of the magnitudes but the price to pay would be a lower image resolution.

In alternative, if it was possible to record new videos, simply the use of high speed cameras, with high resolution, would considerably reduce errors related to the final data since all the peaks of the different magnitudes, even if really short in time, could be detected.

To lower the calibration errors it would also be helpful if the cameras were recording the whole ring so that all the references needed for the set-up of the coordinates system were clearly visible. The use of steady cameras, or at least an improvement of the motion tracking software in taking into consideration the relative movement of the cameras, would increase the data reliability too.

Finally, a larger database of major hits not resulting in knockouts would be needed to draw statistically significant conclusions about the difference between KOs and Other Hits.

## 4.5 Future studies

This work could be of use as the base for further studies about sports-related mild traumatic brain injuries.

It would be interesting to evaluate the kinematics of the struck head not only in the three dimensional resultant but along each one of the coordinates axes. Maybe we would find out that the occurrence of a concussion is dependent on the peak value of just one of the rotational acceleration components and not on all the three of them. In this case, since all the punches taken into consideration in this work were hooks, the study of other types of hits, like uppercuts or jabs, would give us different results that could be used for a comparison of thresholds along different axes.

Another interesting aspect of the phenomenon to evaluate would be the dependence on the history of the match and on the career of the struck boxers. We might find out that a lower value of rotational acceleration is needed to knockout an athlete during the last rounds if he suffered many other subconcussive hits previously in the match. Most likely it would be lower also in the case that the boxer underwent one or more mild traumatic brain injuries during his career, in particular the weeks before the studied match [9].

# 5. Conclusions

In this study we evaluated motion tracking, based only on the video analysis of footages broadcasted by television, as a method to assess the kinematics of a mild traumatic brain injury during a professional boxing match.

From a database, 35 videos of punches were selected and divided into 25 knockouts and 10 other major hits. They were then divided in subgroups according to the frame rate of the cameras used to record them. Finally they were analysed using a proper software called SkillSpector.

Magnitudes like translational and rotational velocities and acceleretions of the hand of the boxer throwing the punch and the head of the opponent were taken into consideration. They were compared with similar values found in previous studies, based on different methods to evaluate mild traumatic brain injuries (concussions) due to impacts in sports such as boxing, American football and ice hockey. This was done in order to get an evaluation of the effectiveness of our method.

Data obtained from knockouts recorded at 90 fps were comparable with the ones found in literature: an average maximum value of head rotational acceleration equal to 8783 $rad/s^2$ (SD 2290 $rad/s^2$) and a mean HIC (Head Injury Criterion) equal to 303,5 (SD 287,8) were consistent with the thresholds for a 80% of probability to get a concussion stated in the the work of Zhang et al. [20] in 2004. Instead data related to cases of punches recorded at a frame rate lower than 90 fps were much lower and therefore not comparable. A significant dependence of the peak values on the sample frequency of the videos was noticed (see Figure 23).

A difference between peak values regarding knockouts and other major hits was also found but our database was too small to make it statistically significant.

We conclude that this method to evaluate the kinematics of sports-related head traumas is effective even though some measures must be taken in order to obtain more precise results. Finally the study of the head movement’s components along the three different axes and the study of the history of the match and the struck boxer’s career would also give us a better understanding of the phenomenon.

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