A METHODOLOGICAL APPROACH FOR SIMULATING MUSCULOSKELETAL LOADING IN THE HEAD AND NECK REGION FOLLOWING BOXING PUNCHES TO THE HEAD

Sven Paldauf[1], Wolfgang Potthast[1], Igor Komnik[1]

Institute of Biomechanics and Orthopaedics, German Sport University Cologne, Cologne, Germany[1]

The aim of various combat sports is to win the competition by throwing repetitive punches predominantly to the opponent's head. These hitting blows can lead to short and potentially long-term adverse health consequences. The aim of the current study is to introduce an approach that estimates 3D punch forces acting on a struck subject's head. The procedure refers to marker-based kinematic measures and subsequently implementing them into a musculoskeletal head-neck model in OpenSim. The results showed reasonable effective mass estimates , whereby the relatively small force magnitudes and the activation of the reserve moments require methodological modifications followed by the validation of the proposed approach.

KEYWORDS: martial arts, load simulation, OpenSim.

INTRODUCTION: Various combat sport styles aim to directly hit the opponent with different body parts, primarily to gather points or to win the match prematurely by knockout. Through the head being one of the target areas, these sports are highly associated with acute head and neck injuries as well as long term impairments related to damage in this region such as e.g. mild traumatic brain injury or Chronic Traumatic Encephalopathy (CTE) (Hammami, 2018; Zazryn, 2009).
The severity of such injuries depends on different factors, including the direction of action as part of different techniques, the duration of the athlete's career, and particularly the punch force magnitude (Gennarelli, 1987; Zazryn, 2009). The relevance of this topic inspired many researchers to measure the head response in the forms of head acceleration following various types of impacts using various measurement devices, primarily using inertia measurement units (Johnson, 1975; Patton, 2016). In addition, the punch forces of the striking athlete were collected to get an insight into the forces that emerge in combat sports (Girodet, 2005; Smith, 2000; Walilko, 2005). Unfortunately, these methods do not consider a three-dimensional force vector and/or only measure the force at the target area using human surrogates. Complex analyses that combine the force direction, the point where force is applied to the head and the load that results in the human head and neck region cannot be performed sufficiently with previous methodological approaches.
The present investigation proposes a method that estimates a three-dimensional force vector following boxing punches using marker-based kinematic data of the head and the punching hand based on equations incorporating the struck boxer's head mass. Ultimately, this approach enables analyzing the loads in the head and neck region by implementing the punch force estimates and the head kinematics into a musculoskeletal multibody model.

METHODS: The following list describes individual methodological steps creating the basis for further analysis of the head and neck loads.

The investigation included a three-dimensional motion analysis (Bonita B10, Vicon Motion Systems Ltd., GB, 250 Hz) of two subjects (striking subject (OFF) vs. struck subject (DEF)).

Retro-reflective markers were attached to OFF’s Head, trunk, right upper limb and boxing glove (right/left forehead, right/left occiput, right/left acromion, manubrium sterni, Corpus sterni, vertebra prominens, proc. spinosus thoracicae 10, tuberculum majus, epicondylus lateralis/medialis humeri, extensor digitorum, proc. styloideus ulnae/radii, glove impact area. Additionally, markers were attached to DEF’s head and trunk (right/left forehead, right/left occiput, right os zygomaticum, right/left angulus mandibulae, right/left acromion, manubrium sterni, corpus sterni, vertebra prominens, proc. spinosus thoracicae 10).

Five punch trials (approx. 15% of striking subject's maximum punch capability) were captured of the right cross and right hook boxing techniques, respectively.
Struck subject's head was scanned in a 3D body scanner (Vitus Bodyscan, Vitronic Dr.-Ing. Stein Bildverarbeitungssysteme GmbH, Ger) to estimate the head mass as the product of volume and density.

A head-neck model (HNM) (HYOID model by Mortensen, 2018) was scaled according to DEF's anthropometry considering body mass, estimated head mass, and a static reference trial.

Calculation of the effective punch mass (m_e) by means of the linear impulse-momentum relationship (Zaciorskij, 2002).

$$m_e = \frac{1}{\Delta V}\int_{t1}^{t2} F dt \quad (1)$$

$\int_{t1}^{t2} F dt$ is the linear impulse of the head from the impact between initial contact (t1) and the instant when the punching hand moves apart from the head (t2).

Calculation of punch force:

$$F_{head} = m_e \times (a_{fist}) \times (-1) \quad (2)$$

Marker trajectories were filtered with a 4th order Butterworth low-pass filter (cut-off 25 Hz).

The locations of the point of force application were considered to be the trajectories of the retroreflective Marker *RTIP*, which was attached on the boxing glove's target area. When *RTIP* was covered, it was recreated using three additional Markers on the fist segment, neglecting the effect of glove compression.

Inverse kinematics was performed using the scaled HNM in OpenSim.

Computed Muscle Control was conducted. Reserve actuators were added to the model to assess further the force estimates and the suitability of the HNM concerning load quantification of the head-neck region following boxing punches.

Extracted parameters: maximum resultant punch force (F_{max}), maximum effective punch mass ($m_{e\ max}$), maximum punch velocity (v_{max}) and velocity before initial contact (v_{pre}). Discrete values are presented as means ± standard deviation. Reserve moments in the form of time series.

RESULTS: The results in Table 1 imply that the mean F_{max} of the hook punches was approximately 26 % lower compared to the cross punches but have a higher standard deviation. The highest punch force was 124 N and was generated by cross 5, whereas the maximum punch force of hook 5 reached a similar magnitude. Furthermore, the force applied to the head by the hook punches lasted only 1/3 of the duration (F_{dur}) of the cross punches, although t_{peak} was the same for both punching techniques. Head mass calculated in section 5.5 resulted in 4.88 kg. The calculation of the effective punch mass based on the head mass of DEF ($m_{e\ max}$) showed to be lower for the hook punches compared to the cross punches. For both cross and hook, v_{max} was almost twice the magnitude of v_{pre}.

Table 1: Discrete parameters during the right cross and hook punches. Mean and standard deviation values are presented.

Punch technique	F_{max} (N)	F_{dur} (s)	T_{max} (s)	$m_{e\ max}$ (kg)	V_{max} (ms^{-1})	V_{pre} (ms^{-1})
cross	106 (14)	0.138 (0.018)	0.010 (0.002)	2.1 (0.31)	2.55 (0.05)	1.28 (0.16)
hook	79 (22)	0.046 (0.005)	0.010 (0.002)	1.76 (0.27)	2.48 (0.13)	1.37 (0.11)

The reserve moments revealed that the pitch reserve moments were generally higher in cross punches than hook punches. Following cross punches, the negative forces of pitch1 (skull-C2 joint) indicate that a flexion moment is applied, whereas in pitch2 (C2-T1 joints), the reserve actuators apply an extension moment. For roll1, the moments were higher in the cross punches. In contrast, roll2 reserves increased in hook punches. Examining the yaw reserves, yaw2 showed a clearly higher duration in the hook punches than cross punches (Figure 1).

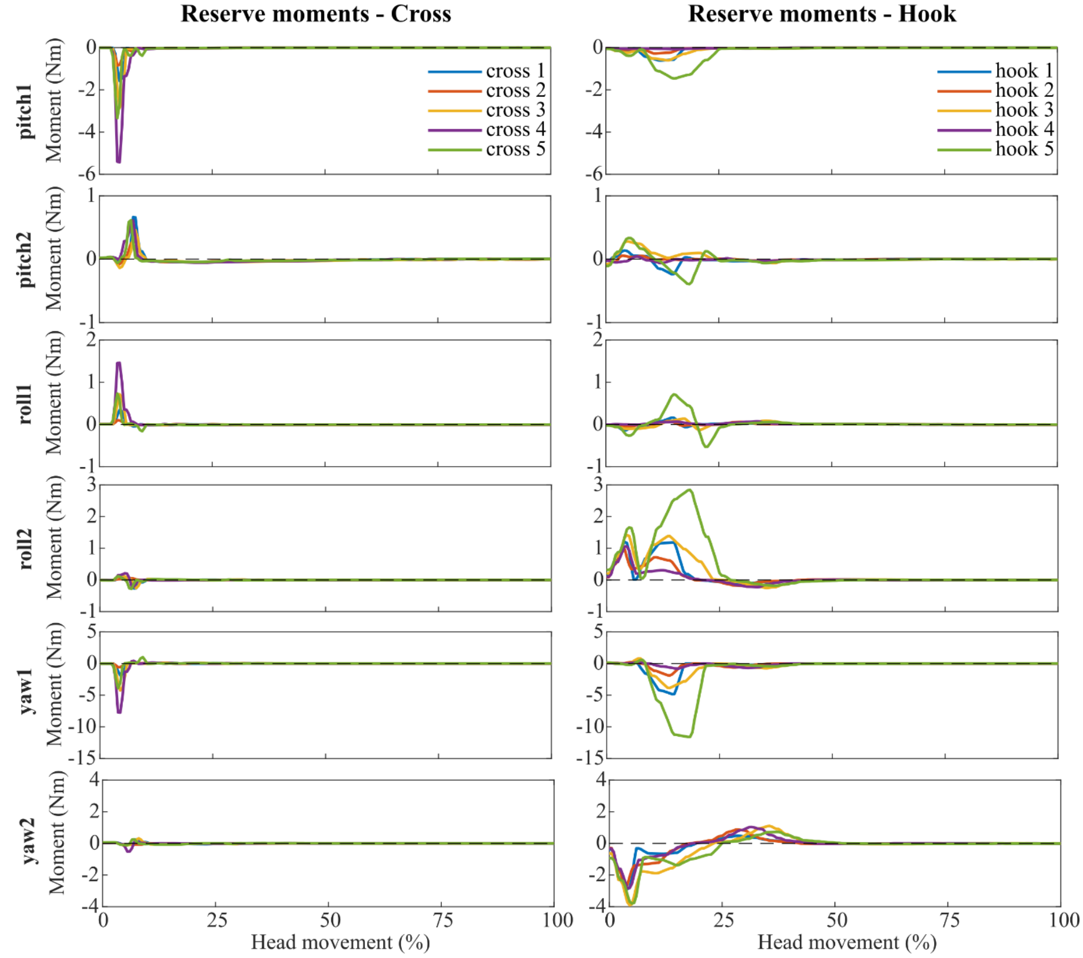

Figure 1: Reserve moments of cross punches (left column) and hook punches (right column) around the main coordinates of the HNM. For pitch, a negative value indicates the application of a flexion moment. For roll, a positive value indicates a right lateral bending moment. For yaw, a positive moment indicates a left axial rotation moment.

DISCUSSION: The analysis concerning the accuracy of the force estimates and therewith related suitability of the presented methodological approach to quantify loading on the head and neck following boxing punches demonstrated the strengths and weaknesses that come along with the present estimation approach.

The maximum effective punch mass of OFF was higher by 16% in cross compared to hook punches. For both punching techniques, maxima were predominantly lower but within one standard deviation of mean values for flyweight (2.3 kg) and light welterweight (2.7 kg) boxers (Walilko, 2005), although OFF (71 kg) would be in a higher weight division. The mentioned study estimated the effective mass using conservation of momentum after impacting a Hybrid III dummy head. Another study estimated the effective mass performing palm strikes to a basketball (Neto, 2007). The effective mass was similar to the findings of the current investigation, ranging from 1.33 kg in novice participants to 2.62 kg in kung fu trained athletes.

At first sight, the calculated force magnitudes seem to be underestimated, but the amount of underestimation cannot be interpreted with the present strategies. The reserve moments solely display if an underestimation is present without making statements about the magnitude of the underestimation. It is generally difficult to compare the force magnitudes ascertained in the current study with the existing literature since previous examiners conducted punch force

measurements mostly at the target surfaces, making it impossible to measure punch forces in combat situations using these devices. Thus, the relatively low punch force values may also be connected to the flexibility of DEF's head and neck region, which was also suggested by other authors (Girodet, 2005). The hardest hook punch, hook 5, reached 10 %, and the hardest cross, cross 5, reached 11 % of directly measured mean punch forces in a boxing competition, measured with pressure sensors incorporated into the glove padding (Pierce, 2006). These relations roughly comply with the instruction to punch DEF with an intensity of 15%.
The HNM was shown to be strong enough to produce the observed movement, making the model suitable for cross punches in the limited force range applied to the model. Only the muscles driving the pitch1 coordinate were slightly too weak to generate an appropriate moment (Figure 1). The relatively high reserve moments in the first 25% of the movement were activated for the hook punches due to the delayed external force application. This is one of the novel approach's major limitations, which is related to measuring with a relatively low frame rate (250 Hz) and glove bulging.

CONCLUSION: The utilized HNM was shown to be feasible to execute the performed analyses for the specific head movements and calculated external forces, encouraging further development of the proposed methodological approach. However, several limitations have to be addressed, including, e.g., the definition of the start and end of an impact as well as the choice of an appropriate effective mass calculation method. After reaching the *maturity* of the methodological approach, including its validation in the near future, it could provide an improved and a rather realistic risk assessment of strikes to the head in various combat sports.

REFERENCES

Hammami, N., Hattabi, S., Salhi, A., Rezgui, T., Oueslati, M., Bouassida, A. (2018). Combat sport injuries profile. A review. *Science & Sports*, 33, 73–79.

Zazryn, T.R., McCrory, P.R., Cameron, P.A. (2009). Neurologic injuries in boxing and other combat sports. *Physical medicine and rehabilitation clinics of North America*, 20, 227-39.

Gennarelli, T.A., Thibault, L.E., Tomei, G., Wiser, R., Graham, D., Adams, J. (1987). Directional Dependence of Axonal Brain Injury due to Centroidal and Non-Centroidal Acceleration. SAE International400 Commonwealth Drive, Warrendale, PA, United States.

Johnson, J., Skorecki, J., Wells, R.P. (1975). Peak accelerations of the head experienced in boxing. *Medical & Biological Engineering*, 13, 396–404.

Patton, D.A. (2016). A Review of Instrumented Equipment to Investigate Head Impacts in Sport. *Applied bionics and biomechanics*, 7049743.

Girodet, P., Vaslin, P., Dabonneville, M., Lacouture, P. (2005). Two-dimensional kinematic and dynamic analysis of a karate straight punch. *Computer Methods in Biomechanics and Biomedical Engineering*, 8, 117–118.

Smith, M.S., Dyson, R.J., Hale, T., Janaway, L. (2000). Development of a boxing dynamometer and its punch force discrimination efficacy. *Journal of sports sciences*, 18, 445–450.

Walilko, T.J., Viano, D.C., Bir, C.A. (2005). Biomechanics of the head for Olympic boxer punches to the face. *British journal of sports medicine*, 39, 710–719.

Mortensen, J.D., Vasavada, A.N., Merryweather, A.S. (2018). The inclusion of hyoid muscles improve moment generating capacity and dynamic simulations in musculoskeletal models of the head and neck. *PloS one*, 13, e0199912.

Neto, O.P., Magini, M., Saba, M.M.F. (2007). The role of effective mass and hand speed in the performance of kung fu athletes compared with nonpractitioners. *Journal of Applied Biomechanics*, 23, 139–148.

Pierce, J.D., Reinbold, K.A., Lyngard, B.C., Goldman, R.J., Pastore, C.M. (2006). Direct Measurement of Punch Force During Six Professional Boxing Matches. *Journal of Quantitative Analysis in Sports*, 2.