CALCULATION AND EVALUATION OF A THREE-DIMENSIONAL FORCE FOLLOWING BOXING PUNCHES ON A DUMMY HEAD

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The current study evaluates an approach that estimates the 3D force acting on a dummy's head and neck construct following boxing punches. The calculation refers to marker-based kinematic measurements, and incorporates the head mass and the estimated effective mass of the striking hand. A total of 2040 punches were compared with measured force values of a six-axial load cell in the upper dummy neck regarding peak force (peakF) and rate of force development (RFD). The two random effect regression models revealed that the calculated force values could significantly predict the measured force values. The results showed reasonable effective mass estimates (2.04±0.41kg) and plausible force values ($peakF_{MoCap}$ = 268.82 ± 83.89N). Ultimately, this approach can be used in real boxing scenarios and enables analysing the loads in the head and neck region by implementing the punch force estimates and the head kinematics into a musculoskeletal multibody model.

KEYWORDS: head impact, boxing, punch force.

INTRODUCTION: Injuries in full-contact sports are frequent and can lead to long-lasting consequences. Considered as the main target of attack in several martial arts the head and neck are mostly injured, with 90% of all injuries in boxing affecting the head-neck region (Hammami et al., 2018). The high proportion of head injuries is concerning, especially taking into account that repetitive head trauma can result in brain degeneration, severe decrease in cognitive function and result in serious disabilities (Hammami et al., 2018). The relevance of this topic inspired many researchers to measure the head response in the form of head acceleration following various types of impacts. One of the most frequently used methods is the examination of head kinematics using different measurement systems, primarily determining head acceleration to assess the impact's severity (Johnson et al., 1975; Patton, 2016; Viano et al., 2005). Regarding quantifying the impact force, in contrast to pure kinematic parameters, most studies used one or more piezoelectric force transducers on differently shaped, stationary target surfaces covered with a pad to determine impact force (Atha et al., 1985; Girodet et al., 2005; Smith et al., 2000). Furthermore, an armed Hybrid III dummy head (Walilko et al., 2005) and an instrumented boxing glove (Pierce Jr et al., 2006) was used to detect the normal force. Ultimately, none of the studies mentioned above used a method for measuring or determining the force with its three force components (Atha et al., 1985; Girodet et al., 2005; Langholz, 2013; Pierce Jr et al., 2006). This is, however, essential for estimating the load to the head and neck joints of the struck boxer by solving the inverse dynamic problem and the corresponding equations of motion. Since, to date, no measurement device is available to measure the punch force with its three components directly at the target area of the struck opponent under real sparring conditions, calculation methods that use kinematic data can provide a valuable methodological approach. Such an estimation is complex, since the acting force is not solely composed of the mass and acceleration of the hand-glove complex, but rather of a combination of hand acceleration and the mass which arises through stiffening of the joints linking the segments of the whole body. This stiffening of joints at the moment of impact improves the momentum transfer from the residuary body parts. The mass finally acting on the target is called the effective mass (Lenetsky et al., 2015). Paldauf et al. (2022) presented a promising approach that ensures the calculation of a three-dimensional force vector, taking into account the head mass and the estimation of the effective mass of the striking hand. Due to the small number of participants (N=2) in their study, the approach could not be tested for plausibility yet. Based on this approach, in the present investigation, a three-dimensional force vector following boxing punches on a dummy's head is calculated using marker-based kinematic data. The results are statistically compared with measured forces from a load cell in the dummy's upper neck. Therefore, the aim of the study is to evaluate this calculation approach and to test the results for physical plausibility for a wide range of intensities.

METHODS: Twenty-eight subjects (10f/ 18m, 26.6 ± 3.2 years, 178.0 ± 8.6 cm, 75.6 ± 12.3 kg) without further experience in boxing participated in this study. The number of participants was estimated by calculating an a priori power analysis. To simulate the most realistic impulse transfer to a human head, the head and neck of a Crahtest-Dummy (THOR-50M, Kistler Instrumente AG, CHE) mounted on a static fixture were used to simulate the punched opponent. The subjects performed several controlled straight boxing punches to the dummy's forehead. To cover a wide range of intensities, the participants punched with a subjectively perceived low, medium and high intensity, with an order of the intensities randomized per subject. For each intensity, two sets of 15 consecutive strikes were performed, resulting in 90 strikes. In correspondence to a regular boxing training and sparring, the subjects wear a boxing glove (12 ounces) to protect their hand and wrist and to ensure a realistic application of force. Kinematic data were collected using a 3D motion capture system (Qualisys, Gothenburg, Sweden) consisting of 13 infrared cameras operating at 500 Hz. Therefore, four retroreflective markers were attached to anatomical landmarks on the subject's arm (shoulder, elbow medial, elbow lateral, forearm) and four markers were attached to the boxing glove. Additionally, eleven markers were placed on the Crashtest-Dummy (skull, jaw and mounting plate). The upper neck of the THOR-dummy is occupied with a six-axis sensor (M55596A, Kistler Instrumente AG, CHE), measuring the forces with 20.000 Hz. Raw data was recorded using the CrashDesigner software (Kistler Group, CHE) and subsequently filtered and down-sampled to match the motion capture data. The center of gravity (CoG) of the dummy's head in the global coordinate system was extracted by performing a Body Analysis using the musculoskeletal modeling software OpenSim graphical user interface (OpenSim 4.4, SimTK, US) with the head-neck model (HYIOD) of Mortensen et al. (2018). Marker trajectories were filtered with a 4^{th}-order Butterworth low-pass filter (cut-off 25 Hz). The velocity (v) and the acceleration (a) of the hand and the dummy's heads CoG are then determined in MATLAB (R2023b, MathWorks, USA) from the position data of the marker points. The effective mass and the force (F_X, F_Y, F_Z) was calculated considering the approach deployed by Paldauf et al. (2022). In the present study, the mass of the head was replaced by the mass of the dummy's head (4.501 kg). The equation neglects the neck portion involved in the impact, including damping of the neck and other forces (e.g., friction) possibly influencing the force transfer. Subsequent, a resultant force vector (F_{Res}) was calculated for both, the calculated force and from the three measured force components acquired by the load cell. For each stroke, the peak force value ($peakF_{Mocap}$, $peakF_{dummy}$) and the rate of force development (RFD_{Mocap}, RFD_{Dummy}) of F_{Res} were then calculated. To check for the physical plausibility of the results, two random effects regression models were conducted to test if the calculated variables ($peakF_{Mocap}$, RFD_{Mocap}) can significantly predict the measured variables ($peakF_{Dummy}$, RFD_{Dummy}). This model was selected since it provided more appropriate AIC (Akaike information criterion) and BIC (Bayesian information criterion) values compared to running a linear regression model. The statistical analysis was conducted across the entire intensity range. Group differences were taken into account, based on the 28 different test subjects. The statistical calculations were carried out using MATLAB (R2023b, MathWorks USA).

RESULTS: A total of 2040 strokes across the intensities range were examined (mean±SD: $peakF_{MoCap}$ = 268.82 ± 83.89 N, $peakF_{Dummy}$ = 338.23±90.72 N). Both regression models were statistically significant and revealed a strong correlation regarding peakF (R^2 = 0.95, $p \leq .000$), and a strong correlation for RFD (R^2 = 0.82, $p \leq .000$). Therefore, the calculated force values ($peakF_{MoCap}$, RFD_{MoCap}) significantly predicted the measured force values ($peakF_{Dummy}$, RFD_{Dummy}). The regression models' main results are displayed in Table 1, whereas Figure 1 visualizes the regression equations of peakF and RDF for the whole force intensity spectrum tested. The Root Mean Squared Error (RMSE) was calculated for the entire sample as well as separately for the first (N=680), second (N=680) and last third (N=680) of the data points in order to identify any varying consistency of the calculation method depending on the impact intensity (Table 1).

Table 1: Results of the mixed-effects regression models.

	slope	intercept	R^2	*p*	RMSE	RMSE(%)	
Peak F	0.988**	77.85**	0.95	≤ .000	39.0	11.53%	
					40.2	12.10%	$RMSE_{1/3}$
					35.6	10.72%	$RMSE_{2/3}$
					41.0	11.38%	$RMSE_{3/3}$
RFD	0.224**	908.57**	0.82	≤ .00	527	16.50%	
					645.2	22.05%	$RMSE_{1/3}$
					400.4	12.45%	$RMSE_{2/3}$
					507.0	14.73%	$RMSE_{3/3}$

Note: ** = *p* ≤.000; The RMSE(%) is presented as a percentage of the respective mean values of the first, second and last third of the data.

DISCUSSION: The aim of the study was to evaluate an approach for calculating the 3D impact force acting on a dummy's head during straight boxing punches, taking into account the effective mass of the punching hand. The mean effective mass (2.04±0.41kg) was slightly decreased compared to the 2.3kg for flyweight and 2.8kg for light welterweight boxers reported by Walilko et al. (2005). However, they studied professional boxers who were asked to punch with maximum effort. This is supported by the study of Neto et al. (2007) performing palm strikes on a basketball, with an effective mass of 2.62kg in kung fu trained athletes and significantly lower effective mass in novice participants with estimates of 1.33kg.

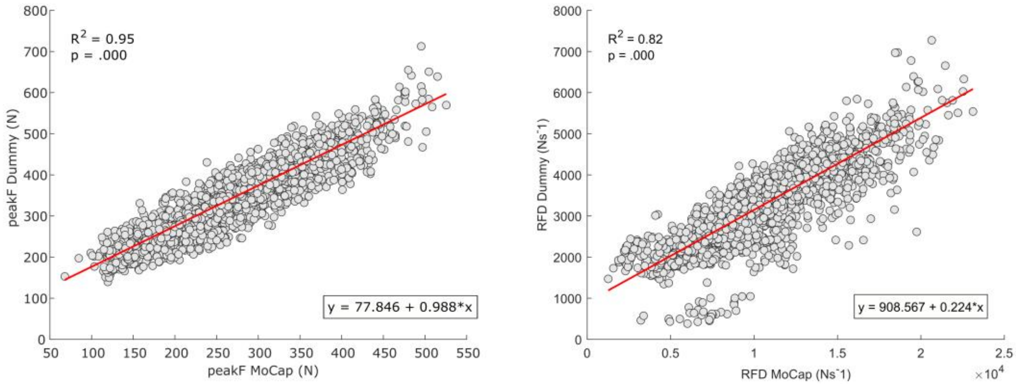

Figure 1: Mixed-effects Regression model for the peakF (left) and RFD (right), with corresponding correlation coefficient, p significance and the fitted regression model equation.

The calculated punch force magnitude was checked for plausibility by statistically comparing them with force data measured using a six-axial force sensor in the dummy's upper neck. Regarding the peakF 95% and RFD 82% of the measured force values could reliably be predicted using the calculated forces. Taking into account the slope and the intercept (Table 1), the predicted and measured $peakF_{Dummy}$ in the dummy's neck area are slightly increased compared to the calculated $peakF_{MoCap}$. The RMSE values indicate that this bias is fixed about 11.53% deviation over the whole measurement range. It should be noted that the calculated force corresponds to the force acting at the application point (PFA_{cal}) on the dummy's forehead, while the reference force was measured in the upper neck load cell. Accordingly, a deviation in the force values was expected. However, from a mechanical point of view, the peak forces at the PFA_{cal} were presumed to be rather higher. This may indicate a slight underestimation of peakF at the PFA_{cal} due to the calculation method. The predicted RFD_{Dummy}, was systematically underestimated by 22.05 to 14.73% (slope = 0.224). The inertia of the head may lead to a delayed transfer of force to the neck, thus decreasing the force gradient. With regard to existing literature, it is difficult to compare the force values ascertained in the current study. Previous examiners usually conducted punch force measurements on the target surfaces, which differed significantly from the present study in terms of mechanical properties (e.g. stiffness, degrees of freedom, shape) and transfer of the results in real boxing scenarios. The relatively low impact force values may, therefore, be related to the more flexible head and neck of the THOR dummy, which has also been suggested by other authors (Girodet et al., 2005; Paldauf et al., 2022). It should be noted that it can only be presumed at this point whether the calculation method is also applicable for higher forces and velocities (e.g. for professional boxers). Due to the complexity of transferring force to the opponent's head during sparring, there remains room in this research field to attain an in-depth understanding of the reaction force acting on the head. However, the consistency of the current study's results, confirmed by the strong regressions with constant RMSEs, supports the plausibility of the calculation method presented. Highlighting the significance of this finding, the presented method can be effectively applied in real boxing scenarios, offering a means to assess punch force during both training and competitions. This can serve as a diagnostic variable for performance and enables the measurement of impact loads on the head. Determining the impact force in combination with kinematic data is crucial for a subsequent analysis using inverse dynamics and musculoskeletal modeling. Using the inverse dynamic modeling approach allows to asses joint loads and specific muscle activation patterns during strikes to the head. However, given the constraints mentioned above, the resulting forces and joint loads may represent modest estimations.

CONCLUSION: This was the first study evaluating a calculation method for estimating the punch force acting on a head as a three-dimensional vector. The results showed reasonable effective mass estimates and plausible force values. Ultimately, this approach can be used in real boxing scenarios and 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. This can contribute significantly to better injury risk assessment and preventive measures in the future.

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