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Heading in Soccer: Does Kinematics of the Head-Neck-Torso Alignment Influence Head Acceleration?

by

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There is little scientific evidence regarding the cumulative effect of purposeful heading. The head-neck-torso alignment is considered to be of great importance when it comes to minimizing potential risks when heading. Therefore, this study determined the relationship between head-neck-torso alignment (cervical spine, head, thoracic spine) and the acceleration of the head, the relationship between head acceleration and maximum ball speed after head impact and differences between head accelerations throughout different heading approaches (standing, jumping, running). A total of 60 male soccer players (18.9 ± 4.0 years, 177.6 ± 14.9 cm, 73.1 ± 8.6 kg) participated in the study. Head accelerations were measured by a telemetric Noraxon DTS 3D Sensor, whereas angles for the head-neck-torso alignment and ball speed were analyzed with a Qualisys Track Manager program. No relationship at all was found for the standing, jumping and running approaches. Concerning the relationship between head acceleration and maximum ball speed after head impact only for the standing header a significant result was calculated (p = 0.024, R^2 = .085). A significant difference in head acceleration (p < .001) was identified between standing, jumping and running headers. To sum up, the relationship between head acceleration and head-neck-torso alignment is more complex than initially assumed and could not be proven in this study. Furthermore first data were generated to check whether the acceleration of the head is a predictor for the resulting maximum ball speed after head impact, but further investigations have to follow. Lastly, we confirmed the results that the head acceleration differs with the approach.

Key words: *injury biomechanics, concussion, impact, heading approaches, kinetics.*

Introduction

For several years heading in soccer has been associated with chronic traumatic encephalopathy (CTE), a degenerative brain disease supposedly resulting from cumulated repetitive concussions or subconcussive impacts, but still with a lack of evidence (Spiotta et al., 2012). The transfer has come from sports such as boxing (McCrory et al., 2007) or American football (Omalu et al., 2010) where the effects of repetitive minor trauma are better investigated. In soccer, the current state of research is still too fragmentary and in many parts does not permit final conclusions. For a better estimation of potential health consequences, it is the task of sports science to investigate extrinsic factors in order to support medicine in interpreting intrinsic mechanisms. Unintentional headers, which lead to the highest acceleration of the head and result from collisions with non-anticipated balls or the player-player or player-ground contact, are said to carry the greatest risk potential (Beaudouin et al., 2018a, 2018b). Intentional headers lead to smaller accelerations (Boden et al., 1998; Caccese and Kaminski, 2016; Levitch et al., 2018), but in return occur more frequently (Caccese and Kaminski, 2016; Hanlon and Bir, 2012). There is little scientific evidence regarding the cumulative effect of purposeful heading, consequently the

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following investigation will refer to the kinematic and kinetic aspects of intentional headers.

The head-neck-torso alignment is considered to be of great importance when it comes to minimizing potential risks while heading (Caccese and Kaminski, 2016; Shewchenko et al., 2005b). At the point of ball contact, neck flexors and extensors should be in co-contraction in order to connect the head and the torso as stably as possible and to minimize the effects of the impact (Bauer et al., 2001; Shewchenko et al., 2005a). The increased mass of a stable head-neck-torso system will result in less acceleration. In a review, Caccese and Kaminski (2016) investigated ways to reduce head acceleration in soccer and concluded, among other things, the need to improve the head-neck-torso alignment. In other words, the larger the nodding motion of the player's head, the greater the resulting head acceleration. Few studies on kinematics when heading are available to answer the outstanding questions. Shewchenko et al. (2005a) combined the kinematics and kinetics of seven soccer players with a numerical model and concluded a reduced head acceleration through an increased muscle pre-tensing and head-neck-torso alignment. Babbs (2001) created mathematical models based upon Newton's second law of motion to illustrate the physics of heading. From his results it can be concluded that muscular coupling is more important for increasing mass than kinematic head-neck-torso alignment (Babbs, 2001). The only comparable investigation on the causal relationship between head-to-trunk kinematics and head acceleration could not proof this assumption (Caccese et al., 2017).

Another issue is to what extent the acceleration of the head predicts the resulting ball speed after head impact. Funk et al. (2011) identified the incoming ball speed as a predictor for the following head acceleration.

In the present study, different heading approaches were performed. The data are to be used to compare and replicate the results of studies that have already been carried out (Bauer et al., 2001; Becker et al., 2018; Lamond et al., 2018).

Therefore, this study considered the following research questions:

(1) Is there a relationship between head-neck-torso alignment (cervical spine angle, head angle, thoracic spine angle) and the acceleration of the head?

(2) Is there a relationship between head acceleration and maximum ball speed after head impact?

(3) Does the acceleration of the head change with a different approach (standing, jumping, running)?

Methods

Participants

The sample size was calculated using G*Power (Version 3.1 for Macinstosh, University of Kiel, Germany). For a linear multiple regression (fixed model, R^2 increase, effect size $f^2 = 0.2$, $\alpha = 0.05$) a minimum group size of 59 persons was calculated (power 0.8).

A total of 60 male active soccer players (18.9 ± 4.0 years, 177.6 ± 14.9 cm, 73.1 ± 8.6 kg) were included. With a mean age of 5.1 ± 1.6 years at the point of club entry, and 6-8 hours of soccer training per week, all players had many years of playing and heading experience. Exclusion criteria were: chronic cervical spine problems, concussion within the last eight weeks, acute injury, acute infection or illness. All participants were informed about the test procedure and gave their written consent. With regard to minors, parents or legal guardians were also informed and gave their written consent. The study was approved by the responsible ethics committee and was conducted following the principles outlined in the Declaration of Helsinki (World Medical Association, 2013).

Measures

Head-neck-torso alignment

Three angles (cervical spine, head, thoracic spine) in three-dimensional space were recorded through motion capture by the Qualisys Track Manager (Version 2.15, Göteborg, Sweden; 200 Hz). Therefore, five super-spherical reflective markers (Noraxon, Scottdale; USA; model: m4, size: 14 mm diameter) were attached to the skin with double-sided adhesive tape (Figure 1) and the following angles were calculated:

- Cervical spine angle: calculated by markers 2, 3 and 4; represents the nodding motion of the player.
- Head angle: calculated by markers 1, 2 and 3; represents the forward head rotation of the

player, by tucking the chin towards the chest, which can be part of the nodding motion.

- Thoracic angle: calculated by markers 3, 4 and 5; represents the degree of arched body tension left at the point of ball contact.

All angles were calculated at the moment of the first ball contact. For this reason three additional markers were attached to the top of the ball to visualize the first movement of the ball caused by impact (defined as the point of ball contact). The system was calibrated by wand type, with an exact wand length of 751.4 mm. Calibration was accepted, if standard deviation of the wand's length measure was below 0.5 mm.

Acceleration

The head acceleration (G) was determined at the point of the initial ball contact using a telemetric DTS 3D accelerometer (Noraxon, Scottdale, USA; size: 22 x 16 x 7 mm; weight: 2.8 g; frequency: 1500 Hz, lowpass filter: 500 Hz; operational range: 6.25 G per axis). It was attached to the occipital area of the head with an individually adjustable rubber band (Noraxon, Scottdale, USA; size: 1000 x 35 mm) (Figure 1). The resulting head acceleration vector *a*, based on the acceleration values of the x, y and z axis, was calculated with the following formula: $a = \sqrt{a_x^2 + a_y^2 + a_z^2}$. Data sequences of the accelerometer and motion capture were recorded synchronously in the same file to get the acceleration values at the moment of initial ball contact.

Header

Three types of headers (standing, jumping, running) were performed in standardized order on a stationary pendulum header (Derbystar, model: Swing, size: 5, diameter 22 cm). The ball had to be headed horizontally to the front as hard as possible for all three types. Players executed three attempts per header type beforehand to minimize learning effects, afterwards three headers of every type were recorded. For all headers maximum ball velocity was calculated. Details of the test set up are presented in Table 1.

Design and Procedure

The study was carried out over a period of 4 weeks (July, 2019) in the biomechanical laboratory of the Department of Sports Science in Kaiserslautern. Testing took about 30 minutes per participant. Anthropometric and soccer specific data were taken after participants were informed about the test procedure and gave their written consent. Data acquisition, processing and analysis were performed by the corresponding author.

Statistical Analysis

To verify the relationship between head acceleration and the angles of the cervical spine, head and thoracic spine a stepwise, multiple linear regression was executed. The relationship between ball speed and head acceleration was analyzed by a linear regression. A one-way ANOVA was applied to verify differences in head acceleration between the different types of heading (standing, jumping, running).

The statistical evaluation was performed using IBM SPSS (Version 25.0 for Macintosh, Chicago, IL, USA). The results are stated as mean values ± standard deviations and 95% confidence intervals. The significance level was set at 5%. To estimate effect sizes, partial eta squared (η_P^2) (Levine and Hullett, 2002) and Cohen's d (*d*) (Cohen, 1988) were computed. All preconditions for stepwise multiple linear regression, linear regression and one-way ANOVA were checked and confirmed.

There were three values for all variables, since each heading type was performed three times. For each approach the trial with the highest head acceleration was registered for further analysis. To run a regression with valid data for the primary aim of the study (head-neck-torso alignment), beforehand all trials were excluded, where the signal was saturated (threshold: 6.25 G) on at least one of the axis (standing header: 28 out of 180; jumping header: 6 out of 180; running header: 86 out of 180).

Results

The descriptive evaluation of all variables is shown in Table 2. Depending on the aims of the study, detailed statistical results are presented in the respective sections.

Relationship: head-neck-torso alignment and head acceleration

No significant relationship between the three angles affecting the head-neck-torso alignment and head acceleration was found for the standing, jumping and running approach (Table 3). Stepwise linear regression showed no significant relationship for the 1st step (cervical spine angle), 2nd step (cervical spine angle, head

angle) and 3rd step (cervical spine angle, head angle, thoracic spine angle).

Relationship: head acceleration and maximum ball speed after head impact

No relationship was detected for jumping headers ($F_{(1,58)}$ = .190, p = .664; R^2 = .003) and running headers ($F_{(1,40)}$ = .414, p = .524, R^2 = .010). For standing headers a relationship was measured ($F_{(1,58)}$ = 5.398, p = .024, R^2 = .085).

Differences: head acceleration for standing, jumping and running headers

A significant difference in head acceleration ($F_{(2,159)}$ = 77.68, $p < .001$, η_p^2 = 0.49) was identified between the three header types: standing, jumping and running (Figure 2). The post hoc Games-Howell test showed significant differences between standing and jumping headers ($p < .001$, d = .81), running and jumping headers ($p < .001$, d = 1.17), although no such differences between standing and running headers (p = .197).
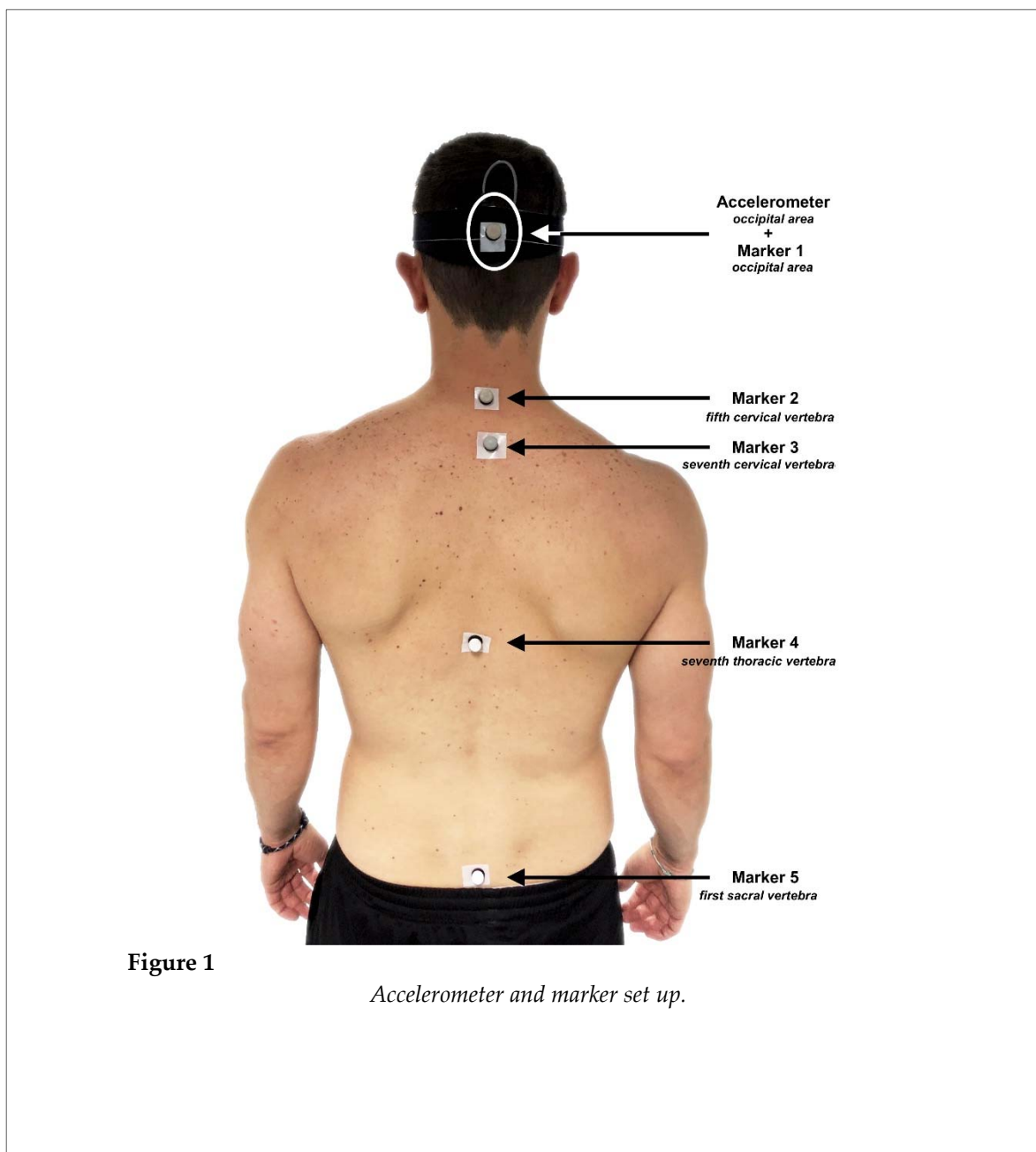

Figure 1

Accelerometer and marker set up.

Table 1

Initial position, take-off and ball height for different types of heading.

Test variable	Standing header	Jumping header	Running header
Initial position	Shoulder-wide stand on a force plate (66 × 60 cm)	Shoulder-wide stand on a force plate (66 × 60 cm)	Walking position at a mark in 3 m distance
Jump	-	Jumping with both legs	Jumping with one or both legs
Ball height	Height of the forehead	One ball diameter above the head	One ball diameter above the head

Table 2

Descriptive values in mean value (M) ± standard deviation (SD) and 95% confidence intervals (CI-95%).

Variable		Standing header N = 60	Jumping header N = 60	Running header N = 42
Head acceleration [G]	M ± SD	6.41 ± 1.31	5.21 ± 1.64	6.80 ± 1.01
	CI-95%	6.08-6.74	4.79-5.64	6.49-7.12
Cervical spine angle [°]	M ± SD	161.35 ± 6.28	160.00 ± 7.18	159.44 ± 6.57
	CI-95%	159.71-162.98	158.10-161.88	159.41-161.48
Head angle [°]	M ± SD	146.03 ± 8.25	144.83 ± 11.22	144.54 ± 8.60
	CI-95%	143.88-148.18	141.88-147.78	141.86-147.22
Thoracic spine angle [°]	M ± SD	164.41 ± 6.27	161.01 ± 7.54	158.10 ± 6.57
	CI-95%	162.77-166.04	159.03-163.00	155.94-160.17
Maximal ball speed [km/h]	M ± SD	22.91 ± 2.74	17.72 ± 2.99	29.87 ± 4.01
	CI-95%	22.20-23.63	16.94-18.51	28.61-31.12

Table 3

Statistical results of the stepwise, multiple linear regression for standing, jumping and running headers. Results are presented as sample size (N), correlation coefficient (R), R-square (R^2), adjusted R-square (Adj. R^2), F-value (F) and significance-value (p).

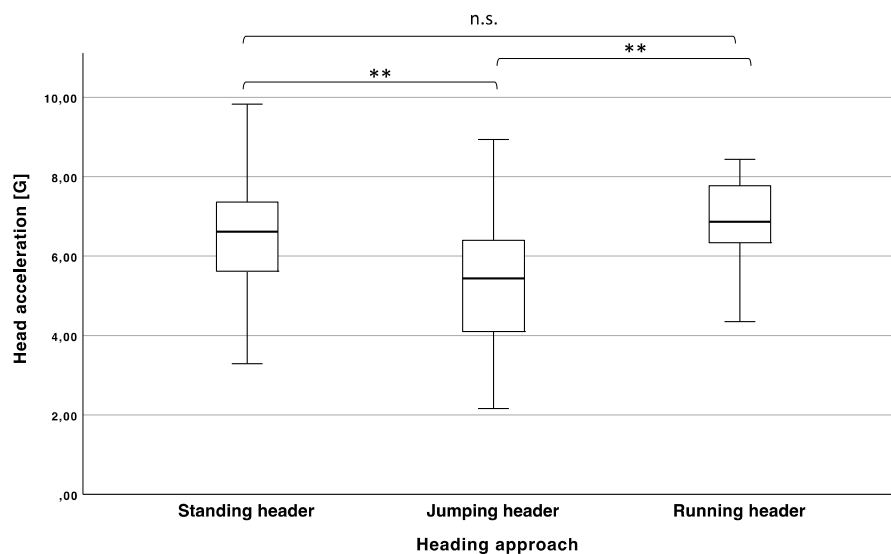|	Standing header	Jumping header	Running header
1. step: cervical spine angle			
N	60	60	42
R	.100	.243	.241
R^2	.010	.059	.058
Adj. R^2	-.007	.043	.034
F	.588	3.625	2.464
p	.446	.062	.124
2. step: cervical spine angle, head angle			
N	59	59	42
R	.121	.292	.243
R^2	.015	.085	.059
Adj. R^2	-.021	.052	.011
F	.414	2.605	1.223
p	.663	.083	.306
3. step: cervical spine angle, head angle, thoracic spine angle			
N	59	58	42
R	.220	.274	.315
R^2	.048	.075	.100
Adj. R^2	-.004	.024	.028
F	.930	.1.465	1.400
p	.432	.234	.258

Figure 2

Differences in head acceleration [G] between standing, jumping
*and running headers (n.s. = no significance, ** = p < .001)*

Discussion

Relationship: head-neck-torso alignment and head acceleration

      The head-neck-torso alignment is one of the first mechanisms mentioned, when physicians and healthcare professionals ask for improvement possibilities for headers in soccer, to reduce the danger potential (Caccese and Kaminski, 2016). Based on Newton's 2nd law of motion ($F = m * a$), the resulting force is a product of mass and acceleration. If the head and the trunk are connected to a rigid system via the neck flexors and extensors, the mass increases and the acceleration should decrease, if the force remains constant (Caccese et al., 2017; Sunami and Maruyama, 2008). In other words, the higher the nodding motion, the higher the head acceleration.

      The relationship between the acceleration of the head and three angles (cervical spine angle,

head angle, thoracic spine angle) at the point of ball contact has not yet been investigated. Anyway, according to previous assumptions the greatest importance is attributed to the cervical spine angle (Babbs, 2001; Caccese and Kaminski, 2016), because it represents best the nodding motion and thus the decoupling of the head-neck-torso segment. For us the head angle is the second most important angle, because it explains the forward-rotation of the head, whereas the cervical spine angle describes the translation of the head towards the ball. Earlier trials and two dimensional studies (Becker et al., 2017; Shewchenko et al., 2005b) showed cases in which the cervical spine angle remained approximately the same, but the player increased the rotational movement of the chin towards the chest, depending on the position of the torso in its surroundings. This is why we calculated the head angle to check its potential relationship. The

thoracic spine angle in general is more important throughout the preparation phase as it builds up the arched body tension (Kirkendall et al., 2001; Sunami and Maruyama, 2008). As to the point of ball contact the aim was to investigate whether there is a relationship between the remaining degree of arched body tension or trunk flexion and the respective head acceleration.

The stepwise multiple linear regression did not show any correlation between the head acceleration at the time of ball contact for the three considered approaches (standing, jumping, running) and the cervical spine angle, head angle and thoracic spine angle. Due to the lack of comparative data, no causally justifiable statements are yet permissible. Nevertheless, it can be assumed from these results that angles and acceleration are influenced by further variables. First and foremost, the EMG activity should be mentioned. Shewchenko et al. (2005b) examined the change in kinetic aspects for a consciously forced "follow-through" and came to the conclusion that the head impact was reduced by 33% if the player consciously headed through the ball. Thus, the present laboratory situation and instructions could have led to an increased activity of M. sternocleidomastoidus (neck flexor) and M. trapezius (neck extensor), which led to compensation of the angular positions (Becker et al., 2017; Shewchenko et al., 2005b). This confirms the assumption of a previous examination that at low ball speeds, even when using a stationary pendulum header, muscular coupling meaning high muscular activity of the neck flexors and extensors can compensate a strong neck flexion at the point of ball contact and is therefore more important than head-neck-torso alignment (Babbs, 2001). Conversely, this means that the importance of the head-neck-torso alignment might only appear with a higher incoming ball speed. Furthermore, there are evidence-based indications that the reproducibility of the player's torso motion, measured over angles, is easier than the head motion. This is comparable to the cervical spine angle and head angle (Shewchenko et al., 2005b). This would be another explanation for the high variability and therefore, the lack of correlation.

Although the influence of the head-neck-torso alignment on the head acceleration needs further investigation, the results are in line with those of Caccese et al. (2017). They investigated the relationship between head-to-trunk range of motion, trunk range of motion and head acceleration in 100 soccer players. They concluded that technique variables, which are largely modifiable, did not predict head acceleration. Instead, greater importance is attributed to head mass, neck girth and neck strength (Caccese et al., 2017).

A possible limitation is the lack of proportionality. In terms of basic research, the aim was to verify whether there is a general relationship between head acceleration and different angles. In further investigations it is urgently recommended to use a static image in a normal-zero position for each player in order to enable better interindividual comparability. In addition, the position of the trunk in its surroundings should be taken into account, as a more horizontal position has to be accompanied by a reduced acceleration (Shewchenko et al., 2005b).

Relationship: head acceleration and maximum ball speed after head impact

First investigations allow the explanation that with increasing speed of the incoming ball the resulting head acceleration increases (Caccese et al., 2016; Funk et al., 2011; Naunheim et al., 2003a). Caccese et al. (2016) showed that purposeful headers from strategic scenarios associated with higher ball speeds such as for example goal kicks and punts will lead to significantly higher head accelerations than from corner kicks, throw-ins and secondary headers. Dorminy et al. (2015) investigated the effect of different ball speeds and linear head impact acceleration in 16 soccer players in field testing. At ball speeds from 48.3 to 80.5 km/h head acceleration increased by almost 20 G, but without being statistically significant ($p = .06$).

From the data available here, it should be verified whether an assumption of this thesis is allowed and whether a higher acceleration of the head at ball contact also predicts the maximum ball speed produced by the player after head impact. Only for the standing header a relationship was measurable, but with small effect. From our point of view a generalization would be inadmissible here; further investigations are necessary. Furthermore, the focus of this study was to examine the relationship between

kinematics and head acceleration at the point of initial ball contact. Other investigations showed that the maximum acceleration did not necessarily occur during the initial phase of ball contact (Becker et al., 2018; Naunheim et al., 2003b), since ball contact lasts approximately 20 ms only (Kerr and Riches, 2004). The following investigations should therefore compare maximum acceleration with maximum ball speed instead of comparing the acceleration at the time of the initial ball contact (Naunheim et al., 2003b; Spiotta et al., 2012), which should be mentioned as a limitation of the present data.

Funk et al. (2011) compared (N = 20) head acceleration at different ball speeds (18.0, 30.6, 36.0 and 41.4 km/h); head acceleration increased continuously (6.8, 15.0, 18.0 and 21.0 G). If one looks at the average accelerations of this study (jumping headers: 4.36 G, standing headers: 6.01 G, running headers: 7.10 G) and ball speeds (jumping headers: 17.71 km/h, standing headers: 22.79 km/h, running headers: 29.61 km/h), a plausible scheme can be recognized despite the lack of significant correlation. Nevertheless, the data also give reason to adhere to training recommendations that novices should practice with slower ball speeds for safer training of the different heading techniques (Caccese and Kaminski, 2016).

Differences: head acceleration for standing, jumping and running headers

Before differentiating between special techniques of ball handling such as clearing header, shooting header, passing header and flick-on (Bauer et al., 2001; Mehnert et al., 2005; Spiotta et al., 2012), the header can be categorized according to its approach: standing, jumping and running (Bauer et al., 2001; Becker et al., 2018; Mehnert et al., 2005). The next step would be to apply one of the special techniques mentioned above.

The results show that the acceleration of the head differs significantly between the different types of heading. They are greatest in the running header (6.80 G), followed by the standing header (6.41 G) and finally the jumping header (5.21 G), which is consistent with the results of earlier investigations (Bauer et al., 2001; Becker et al., 2018). Due to momentum created from running (Mehnert et al., 2005) before the ball is hit, the acceleration of the head is greatest with the running header. The hypothesis formulated by Bauer (2001) that more mass is applied to the ball during the running approach and that the acceleration of the head must therefore be reduced, can be rejected after these results and former investigations (Bauer et al., 2001; Becker et al., 2018).

Contrary to the original assumption (Becker et al., 2018), it seems to be confirmed that the header from the jumping approach, without a run-up, as it can occur for example after a goalkeeper's punt, is clearly more demanding in terms of coordination than the header from the standing approach. Therefore the head acceleration was 1.2 G higher and the maximum ball speed produced was 5.2 km/h higher on average, which is in line with other results (Becker et al., 2018).

Future investigations should consider comparing head accelerations of standing and jumping headers with a similar outgoing ball speed. This might give insight whether coordinative aspects have an influence on the compensation of the head impact. This would support the thesis that the heading technique should be taught systematically and one should not learn from "learning by doing". Furthermore, future studies are recommended to use an accelerometer with a higher threshold.

General study limitations

These findings extend only to male, amateur soccer players. Missing variation across participants in terms of comparable header experience in this cohort, might have influenced the results. Moreover the stationary pendulum header might not be challenging enough, which means that higher incoming ball speeds are necessary to investigate these potential relationships. The primary aim of the study was to investigate the general relationships between head-neck-torso alignment and head acceleration. The secondary aim was to examine the relationship between head acceleration and the ball speed after head impact. Furthermore, the recorded data were used to investigate the differences between the heading approaches. In this case, it can be assumed that the absolute acceleration values, especially for the standing (28 excluded trials) and running (86 excluded trials) approach, would have been higher even though the ANOVA already showed a significant

difference. Nonetheless, the generalizability of the absolute head accelerations measured is limited, although after a comparison with accelerated balls of low velocity (Funk et al., 2011) they seem appropriate.

Conclusions

The relationship between head acceleration and head-neck-torso alignment is more complex than initially assumed and could not be proven in this study. Further kinematic investigations are urgently needed and should include a time-synchronous investigation of the EMG activity in order to have an objective view of potential compensation mechanisms. Thus it could be clarified whether the muscular coupling is more important than the head-neck-torso alignment (Babbs, 2001; Caccese et al., 2017; Lynch and Bauer, 1996).

Various studies support the hypothesis that the speed of an incoming soccer ball is a predictor for the head acceleration occurring as a result of it (Funk et al., 2011; Dorminy et al., 2015; Naunheim et al., 2003a). Here first data were generated to check whether the acceleration of the head is also a predictor of the resulting maximum ball speed after head impact. For the standing header a relationship with a little effect could be proven, yet further investigations have to follow.

The present results support the thesis of other studies that there is a difference between various heading approaches (Bauer et al., 2001; Becker et al., 2018). A header from a safe and stable position and lower coordinative demands leads to a higher power development of the athlete and therefore, a higher acceleration of the head, compared to the jumping header in this set-up. If the momentum is increased by adding some steps (Bauer et al., 2001) or a start-up run (Becker et al., 2018), as it is the case for running headers, a further increase of head acceleration should be expected.

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