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Original Article

Cervical Muscle Activation Characteristics and Head Kinematics in Males and Females Following Acoustic Warnings and Impulsive Head Forces

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Abstract—Sex, head and neck posture, and cervical muscle preparation are contributing factors in the severity of head and neck injuries. However, it is unknown how these factors modulate the head kinematics. In this study, twenty-four (16 male and 8 female) participants experienced 50 impulsive forces to their heads with and without an acoustic warning. Female participants demonstrated a 71 ms faster ($p = 0.002$) muscle activation onset compared to males after warning. The magnitude of muscle activation was not significant between sexes. Females exhibited 21% ($p < 0.008$) greater peak angular velocity in all force directions and 18% ($p < 0.04$) greater peak angular acceleration in sagittal plane compared to males. Females exhibited 15% ($p = 0.03$) greater peak linear acceleration compared to males only in sagittal flexion. Preparation attenuated head kinematics significantly ($p < 0.03$) in 11 out of 18 investigated head kinematics for both sexes. A warning eliciting a startle response 420 ms prior to the impact resulted in significant attenuation of all measured head kinematics in sagittal extension ($p < 0.037$). In conclusion, both sex and warning type were significant factors in head kinematics. These data provide insight into the complex relationship of muscle activation and sex, and may help identify innovative strategies to reduce head and neck injury risk in sports.

Keywords—Head kinematics, Neck muscle, Directional acoustic warning, mTBI, Startle, Posture, Co-contraction.

ABBREVIATIONS

EMG	Electromyography
MVC	Maximum voluntary contraction
$T_{(\text{Pre-Imp-Onset})}$	Time of pre-impact muscle activation onset
$\text{EMG}_{(\text{Pre-Imp-max})}$	Maximum EMG amplitude in pre-impact
$T_{(\text{Pre-Imp-Max})}$	Maximum EMG time in pre-impact
$\text{EMG}_{(\text{Imp})}$	EMG amplitude at the time of impact
$\text{EMG}_{(\text{Post-Imp-Max})}$	Maximum EMG amplitude in post-impact
$T_{(\text{Post-Imp-Max})}$	Maximum EMG time in post-impact
PAV	Peak angular velocity
PAA	Peak angular acceleration
PLA	Peak linear acceleration
LMM	Linear mixed model

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INTRODUCTION

Sport-related concussions occur at an alarming rate, with nearly 4 million incidents a year in the United States. Female athletes experience 10 to 250% more concussions compared to male athletes depending on the sport.[3,8,11,26,32,41,46,48] Female athletes experience higher head kinematics after a head impact or applied force,[3,8,11,32,41,46,48] and researchers hypothesize that the anthropometric difference in neck girth, head-neck segment length, head-neck segment mass, neck strength, and body weight are responsible for the greater head kinematics.[32,39] Alsalaheen *et al.*[3] reported significantly higher peak sternocleidomastoid muscle activation in female participants than males during sagittal extension and concluded that females used a different strategy to mitigate impulsive head forces. However, more investigation of multi-muscle activation and head rotation directionality is warranted to better understand differences in sport-related concussion risk factors between male and female athletes.[3]

Knowledge about an incoming impact is a significant contributing factor in attenuating head kinematics.[12,13,36,40,48] Researchers have reported that 70% of sport-related concussions occur when the individual is either unprepared or has poor posture at the time of contact.[27] Athletes reduce their risk of injury when they have adequate spatial knowledge of their surroundings.[2,12,34,41] There have been efforts to develop a smart helmet capable of predicting and warning players of impending severe collisions and potentially reducing the risk of sport-related concussions.[4,20,29,33,37]

Recently, Homayounpour *et al.*[18,19] reported significant changes in muscle activation, head posture, and head kinematics in male volunteers following different voluntary acoustic warnings of impending head impulse forces. Females are known to have different reaction times and anthropometrics than males,[1,3,8,21,23,32,41,46,48] so it is unknown whether the findings presented by Homayounpour *et al.*[18,19] are generalizable to females. To investigate this, we recruited female and male participants and performed the same protocol mentioned previously for voluntary warnings. We tested the following hypotheses in this study: (1) Females will have different muscle activation characteristics compared to males, both before and after the applied force, for warned and unwarned head impulses; (2) Females will have significantly higher peak linear acceleration, peak angular velocity, and peak angular acceleration compared to males for warned and unwarned head impulses; (3) Head kinematics will be significantly reduced for warned head impulses compared to unwarned, regardless of sex. Homayounpour *et al.*[19] also reported that participants reached higher peak muscle activations with a startling stimulus, but the average muscle activation at the time of impact was not significantly different compared to a non-startling stimulus, likely due to the long time delay between the startle warning and the time of impact (1000 ms).[19] Therefore, in this study, we shortened the time interval between startle warning and the impulsive force to 420 ms. This alteration resulted in the impulsive head force occurring near the maximum involuntary muscle activation, creating the greatest potential to reduce head kinematics from an acoustic warning system. We hypothesized that (4) involuntary neck muscle co-contraction from a startle stimulus would result in a greater reduction in head kinematics compared to voluntary neck muscle co-contraction.

MATERIALS AND METHODS

Fifteen participants (9 female and 6 male) were recruited with the same protocol mentioned in Refs. [18,19]. Participants gave voluntary consent according to the University of Utah Internal Review Board (IRB: 94138) protocol. Participants were a combination of collegiate students and student-athletes and were included if they had no history of concussions, neck injuries, and were able to respond to verbal instructions and an audible stimulus. Data from one female participant was excluded because of an error in the mouthguard data collection. Data from these 14 participants were aggregated with data from a past study[19] investigating 10 male participants, making the final study population 8 females and 16 males ($N = 24$).

Instrumentation

Briefly, the participants were instrumented with 8 EMG sensors (Tringo, Delsys) bilaterally over the sternocleidomastoid (SCM), hyoid (HYO), semispinalis capitis (SEMI), and splenius capitis (SPL) muscles, as depicted in Fig. 1. Participants were secured to a chair using adjustable straps to minimize torso motion. The participant's headgear included noise-canceling headphones and was attached to four masses (1.2 kg) that could free fell for 62 cm.[19] These masses were located in the front, back, left, and right of the participant and applied impulsive forces in sagittal flexion, sagittal extension, and coronal lateral-flexion to the left and right, respectively. Load cells (2 kHz, S-Type, PCB, NY) were in line with each mass to measure the applied force to the head. An instrumented mouthguard (Vector, Athlete Intelligence, WA, USA) collected the head's kinematics at the location of the mouthguard: linear acceleration, angular acceleration, and angular velocity. The mouthguard has been validated, and properties explained by Camarillo *et al.*[9] Each participant wore earbuds (ER3XR, ETYMOTIC, IL) that delivered the acoustic warnings.

Test Condition

Each participant experienced 50 safe head impulsive forces (< 221 N) following a warning (Directional, Non-Directional, Startle-Long, and Startle-Short) or without warning (Unwarned). The Directional and Non-Directional warnings played at 72 dB for 500 ms starting 1000 ms before the applied force. The four Directional warnings notified the participant about the impulsive force direction, whereas the Non-Directional warning was not associated with any force direction. Participants were asked to move against the pull

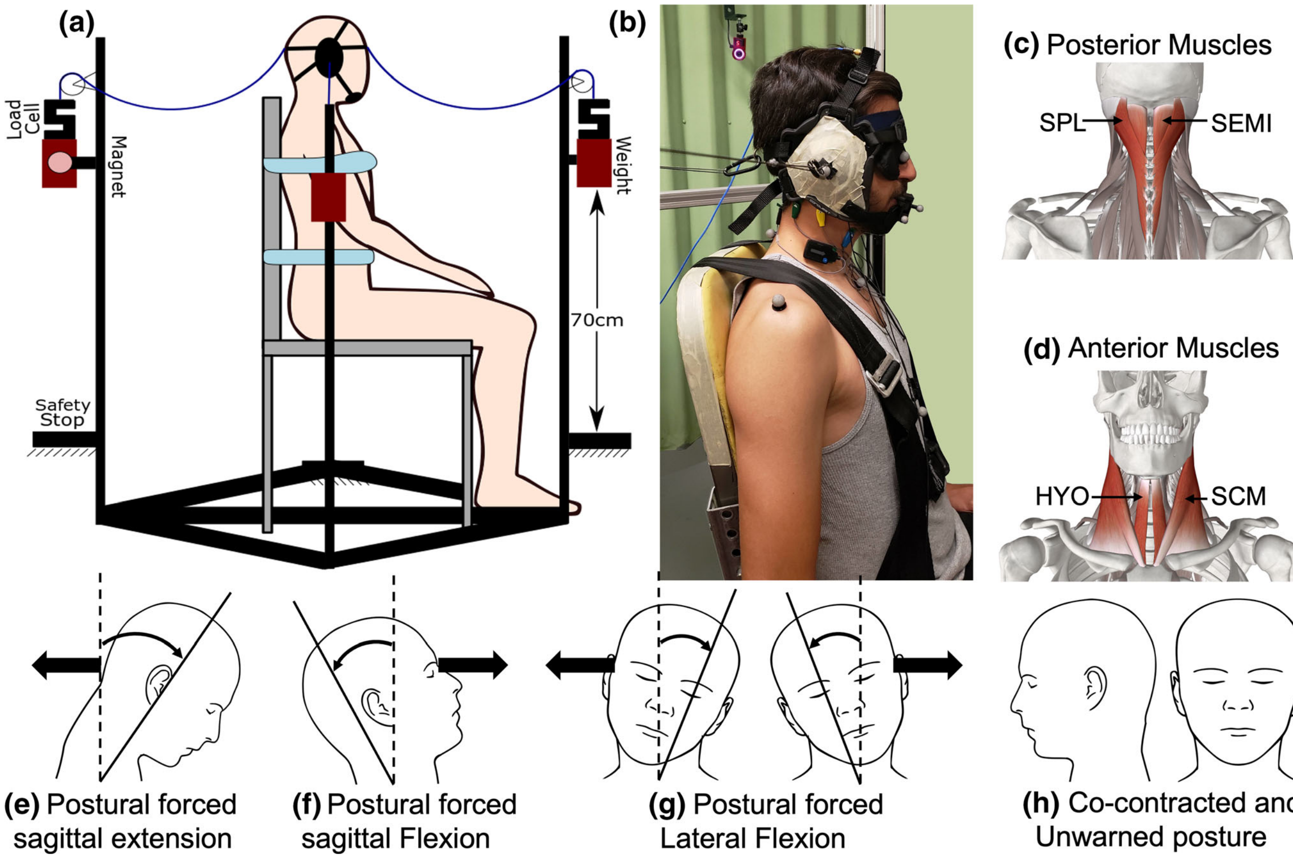

FIGURE 1. (a) Schematic of the testbed.[18,19] The testbed includes four weights, allowing for impulsive loads to be applied in four different directions without modifying the experimental setup. Impulsive forces were applied with a 1.2 kg weight, attached to a headgear using Kevlar cable. The Kevlar cable has slack to allow the mass to free fall on the linear guide for 60 cm and then pull the head. A safety stop was placed 10 cm after the end of the string to make sure the neck would not be overextended. Participants were strapped to the chair to minimize trunk movement, with their hands placed on their laps. (b) Instrumented participant: headgear was sized for each subject before the test to reduce slipping. The noise cancellation headphones on the headband, the earbuds, and the blindfold removed environmental acoustic and visual cues for participants in test trials. (c) EMG sensors were placed bilaterally over the posterior muscles, semispinalis capitis (SEMI) and splenius capitis (SPL), and (d) anterior muscles, sternocleidomastoid (SCM) and hyoid (HYO), muscles. Posture in different test conditions: (f) forced sagittal extension, (e) forced sagittal flexion and (g) forced lateral flexion to the left and the right with postural changes and, (h) participant remained in the neutral posture for the co-contracted and unwarned conditions and were not informed about the direction of the force. The arrows show the positive direction in $Pos_{(Imp)}$ for each force direction.

direction in Directional trials and isometrically co-contract their neck muscles after the Non-Directional warnings, Fig. 1. Appropriate responses, based on these instructions, were verified using video recordings of Directional and Non-Directional trials. Startle trials (Startle-Short and Startle-Long) played at 115 dB for 500 ms, capable of evoking a startling response in participants. By testing the first 10 participants, we established the timing of the peak muscle activity by applying force 1000 ms after the startling stimulus (Startle-Long). Based on our results in Ref. 19, we applied the impact at 420 ms (Startle-Short) for the second 14 participants to test the effect on kinematics if the applied force occurred when the muscles were closer to the peak activation levels. All other test conditions were identical between this study and Ref. 19. Startle trials were dismissed if muscle activation did not occur within the first 100ms after playing the startling stimulus.

Test Procedure

Baseline Trials and Acclimation

Participants performed two trials of maximum voluntary contraction (MVC). With the headband attached via cables to a fixed load cell, participants were asked to pull with maximum force in sagittal extension, sagittal flexion, and right and left lateral flexion for 4 s. The maximum measured force in each direction was recorded as the participants' strength in that direction. Then, with a neutral posture, participants were asked to isometrically co-contract their neck muscles for four seconds.

After the MVC trials, the Directional and Non-Directional warnings were played three or more times to familiarize participants with the sounds. Then five impulsive forces with warnings (4 Directional and 1 Non-Directional) were performed on the participant to minimize the learning and habituation effect and were not included in the results. The warning type, direction, and timing were explained to the participant before the warning was played. These trials were not included in the data analysis due to the possibility of habituation.[43]

Test Trials

The 15 impulsive forces were applied following either Non-Directional and Directional warnings in random order. Immediately after these 15 impulsive forces, 30 forces were applied, following either with a warning (Startle, Directional, and Non-Directional) or without warning (Unwarned). The 30 trials were performed in random order. Overall, participants experienced 18 Directional warnings, 12 Non-Directional warnings, 5 Startle warnings, and 10 Unwarned trials. The MVC trials were repeated after the impulsive tests to check for fatigue.

Data Analysis

Muscle Activation

EMG data were high pass filtered using an 8th order Butterworth filter at 30 Hz to remove motion artifacts before calculating the root mean square (RMS) using a zero-phase 50 ms moving window. The baseline EMG, defined as the minimum muscle activation for a 2 s period after the warning, was subtracted from the EMG signal and then normalized based on the calculated MVC value for each muscle. The amplitudes were reported in %MVC. The EMG features, EMG onset time ($T_{\text{(Pre-Imp-Onset)}}$), EMG maximum activation time and amplitude ($T_{\text{(Pre-Imp-Max)}}$ and $\text{EMG}_{\text{(Pre-Imp-Max)}}$), EMG amplitude just prior to the head impulse ($\text{EMG}_{\text{(Imp)}}$) and, maximum EMG time and amplitude within 300ms after the head impulse, ($T_{\text{(Post-Imp-Max)}}$ and $\text{EMG}_{\text{(Post-Imp-Max)}}$), were calculated as depicted in Fig. 2.[19] EMG artifact due to contact of the headgear's earpiece or poor connection between the skin sensor accounted for 10% of the EMG data and were removed prior to analysis. Muscles were grouped into retraction (muscles pulling against the force direction) and rebound muscle (muscles stabilizing the head after retraction). For post-impact EMG outcomes, the eight muscles monitored during the protocol were combined to make four groups: anterior (bilaterally HYO and SCM), posterior (bilaterally SPL and SEMI), right (R-HYO, R-SCM, R-SEMI, R-SPL), and left (L-HYO, L-SCM, L-SEMI, L-SPL).[19] As an example, anterior muscles are assigned as retraction, and posterior muscles are assigned as rebound muscles in the sagittal extension force direction. Muscle grouping will reduce the effect of potential cross-talk between the muscles as well.

Kinematics

Head angular acceleration was low-pass filtered at 12 Hz using a 4th order Butterworth filter. Peak linear acceleration (PLA), peak angular velocity (PAV), and peak angular acceleration (PAA) were calculated from the resultant of the 3D kinematic data. The time between PLA and PAA/PAV was also calculated. Due to head positioning with and without warnings, the drop height of the mass could vary between participants and within trials among the participants. Therefore, the kinematics were normalized by the energy of the applied force as dictated by the drop height of the mass. The kinematics were adjusted based on the measured free-fall height in each trial.[18] The details are explained in the supplementary materials.

Statistics

Linear mixed models (LMM) were used to describe the dependent variables in this study. In all the mentioned models, the participant was assigned as the random effect. We tested the effects of sex, warning type (Non-Directional, Directional, Unwarned), and the interaction between sex and warning type on muscle activation and head kinematics. We also tested if involuntary muscle co-contraction from startle stimuli with short (420 ms, Startle-short) and long (1000 ms, Startle-long) warning times were more effective than voluntary Non-Directional warnings on the reduction of head kinematics regardless of sex. Post-Impact EMG activation data were separated into sagittal extension, sagittal flexion, and coronal lateral flexion (left and right) force direction groups. Model assumptions were validated using the normality test of the residuals. Multiple comparisons were controlled by Benjamini–Hochberg method.[6] All statistical analysis was performed using MATLAB 2020a (MathWorks, Natick, MA, USA).

RESULTS

A summary of the anthropometric and strength data from the remaining 24 participants is provided in Table 1. Male participants were significantly taller, had greater neck circumference, and greater neck strength in sagittal extension and flexion. There were no significant differences in body weight, BMI, age, and

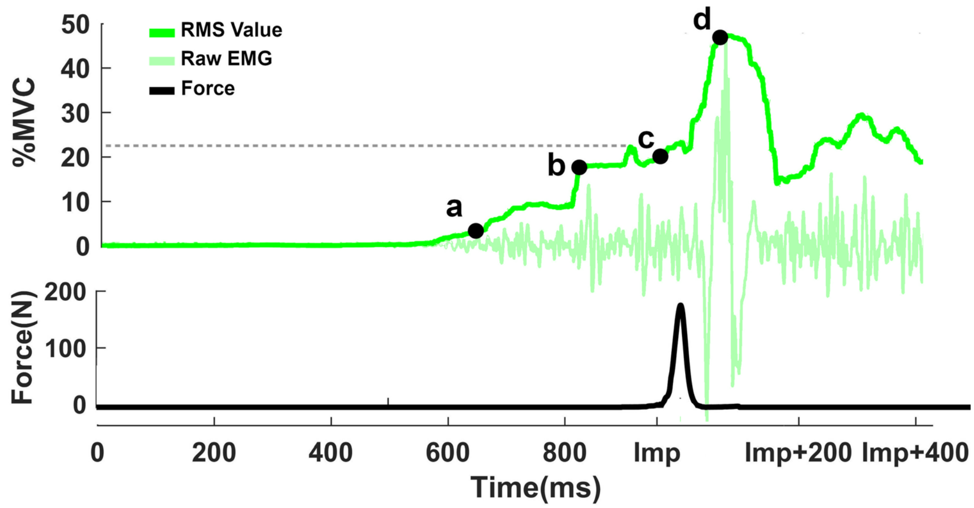

FIGURE 2. A sample of EMG amplitude for the SCM muscle and the force profile in that trial. The warning started playing at time = 0 and impact happened at the time = Imp. (a) $T_{(Pre\text{-}Imp\text{-}Onset)}$ represented the first time that the value of muscle activation reached 3% MVC. The dashed line indicates the absolute maximum value after the warning and before the impact for that test trial for the SCM muscle. (b) $T_{(Pre\text{-}Imp\text{-}Max)}$ defined when the EMG amplitude reached 70% of its maximum amplitude, $EMG_{(Pre\text{-}Imp\text{-}max)}$, before the head impulse in that trial, (c) $EMG_{(Imp)}$ represented EMG amplitude at the onset of the force, and (d) $T_{(Post\text{-}Imp\text{-}Max)}$ is the time of peak EMG activation, $EMG_{(Post\text{-}Imp\text{-}Max)}$, after the head impulse. The times associated with points a, $T_{(Pre\text{-}Imp\text{-}Onset)}$, and b, $T_{(Pre\text{-}Imp\text{-}Max)}$, are reported relative to the time of warning, $t = 0$. The time at point D, $T_{(Post\text{-}Imp\text{-}Max)}$ was reported relative to the time of impact, t = Imp.[19]

TABLE 1. Anthropometric and neck strength measurements.

	Anthropometric (mean (SD))				
	Number	Height(cm)	Weight(kg)	BMI(kg/m^2)	Age(years)
Male	16	180.0 (5.4)	74.4 (7.8)	22.9 (2.1)	25.3 (3.1)
Female	8	168.8 (6.0)	67.7 (9.0)	23.8 (3.3)	23.5 (3.1)
p Value		**< 0.001**	0.06	0.434	0.172
	Neck strength and circumference				
	Sag. Ext.(N)	Sag. Flex.(N)	Lat. Right(N)	Lat. Left(N)	Neck-Cir(cm)
Male	180.2 (41.2)	166.7 (30.9)	131.0 (25.9)	136.0 (27.2)	37.5 (2.1)
Female	146.9 (26.2)	125.0 (21.6)	125.0 (23.3)	125.6 (18.5)	31.9 (1.5)
p Value	**0.042**	**0.002**	0.571	0.322	**< 0.001**

Significant values (p value < 0.05) are bolded.

lateral neck strength between the males and females. The measured head impulse forces to the males (181.1 ± 2.4 N) was significantly greater than the measured head impulse forces to females (165.6 ± 3.9 N, $p < 0.001$). We tested for a training effect on kinematics and EMG responses and did not find it significant in the models.

Pre-impact EMG Activation Due To Warning

The time between the warning and onset of muscle activation ($T_{(Pre\text{-}Imp\text{-}Onset)}$) for female participants was 72 ms faster compared to male participants ($p < 0.002$, Table 2), but sex was not a significant effect of $EMG_{(Pre\text{-}Imp\text{-}Max)}$ and $T_{(Pre\text{-}Imp\text{-}Max)}$. Directional warnings had significantly ($p < 0.001$) faster muscle activation times ($T_{(Pre\text{-}Imp\text{-}Onset)}$, Dir: 479 vs. Non-Dir: 551ms; $T_{(Pre\text{-}Imp\text{-}Max)}$, Dir: 785 vs. Non-Dir: 729 ms) compared to Non-Directional warnings, but resulted in significantly lower muscle activation amplitudes prior to impact ($EMG_{(Pre\text{-}Imp\text{-}Max)}$, Dir: 13.2%MVC vs. Non-Dir: 19.9%MVC).

Impact and Post-impact EMG Activation

There were no significant differences between sexes in $EMG_{(Imp)}$, $T_{(Post\text{-}Imp\text{-}Max)}$, and $EMG_{(Post\text{-}Imp\text{-}Max)}$ in any direction, with any warning type, with either retraction or rebound muscles (Table 3). $EMG_{(Imp)}$ was significantly higher in Non-Directional trials

TABLE 2. Pre-impact muscle activation due to acoustic warnings.

	$T_{(Pre\text{-}Imp\text{-}Onset)}$ (ms)		$EMG_{(Pre\text{-}Imp\text{-}Max)}$ (%MVC)		$T_{(Pre\text{-}Imp\text{-}Max)}$ (ms)	
	Mean (SE)	*p* value	Mean (SE)	*p* value	Mean (SE)	*p* value
Non-Dir (Male)	550.9 (15.2)		19.9 (1.7)		784.6 (16.2)	
Female (Beta)	**− 72.2 (23.9)**	0.005	2.2 (2.8)	0.548	− 48.8 (25.6)	0.097
Dir (Male)	**479.5 (9.0)**	0.001	**13.2 (0.8)**	0.001	**729.0 (9.2)**	0.001

Voluntary muscle activation features including EMG onset time, $T_{(Pre\text{-}Imp\text{-}Onset)}$, and maximum EMG time and amplitude, $T_{(Pre\text{-}Imp\text{-}Max)}$ and $EMG_{(Pre\text{-}Imp\text{-}Max)}$. Female (beta) row indicates the amount of change in the respective value compared to male participants regardless of warning types.
Significant values (*p* value < 0.05) are bolded.

(21.2%MVC) than Directional trials (14.0%MVC), and both conditions were significantly higher than the Unwarned trials (0.9%MVC). $T_{(Post\text{-}Imp\text{-}Max)}$ was significantly faster for Directional (118 ms) and Non-Directional trials (117 ms) compared to the Unwarned (152 ms) trials (except retraction muscles in Non-Directional with sagittal flexion force). $T_{(Post\text{-}Imp\text{-}Max)}$ was not significantly different between the Non-Directional and Directional trials for any muscle group or direction. $EMG_{(Post\text{-}Imp\text{-}Max)}$ was generally higher with Non-Directional (60%MVC) warnings compared to Unwarned conditions (48%MVC) in both retraction and rebound muscles, but not all of the comparisons were significant (Table 3). $EMG_{(Post\text{-}Imp\text{-}Max)}$ was generally lower for both muscle groups when comparing Directional warnings to Non-Directional warnings, but it was only significant for rebound muscles.

Head Kinematics

Head kinematics were generally higher in female participants (Figure 3, Online Table 7). Female participants had significantly higher PAV than males (+ 1.1 rad s^{-1}, $p < 0.007$). PAA was significantly higher in sagittal extension (+ 54 rad s^{-2}) and sagittal flexion (+ 47 rad s^{-2}), but not in the lateral direction (+ 29 rad s^{-2}). PLA significantly increased in female participants in sagittal flexion (+ 7.5 m s^{-2}), but not in sagittal extension and lateral flexion.

Directional (4.7 ± 0.1 rad s^{-1}) and Non-Directional warnings (4.0 ± 0.1 rad s^{-1}) significantly attenuated PAV compared to Unwarned conditions (5.2 ± 0.2 rad s^{-1}) for both sexes and all force directions ($p < 0.004$), except Directional warnings in sagittal flexion. Directional (48.9 ± 2.1 m s^{-2}) and Non-Directional (49.8 ± 2.4 m s^{-2}) warnings significantly attenuated PLA compared to Unwarned conditions (55.1 ± 3.0 m s^{-2}) for both sexes and force directions ($p < 0.03$), except Non-Directional warnings in sagittal flexion and Directional warnings in lateral flexion. PAA in the sagittal plane significantly ($p < 0.035$) increased with Directional warnings (Ext: 258 ± 8 rad s^{-2} and Flex: 254 ± 9 rad s^{-2}) compared to Unwarned conditions (Ext: 240 ± 16 rad s^{-2} and Flex: 197 ± 14 rad s^{-2}), but significantly ($p < 0.0001$) decreased in the lateral directions (Unwarned: 326 ± 10 rad s^{-2}; Non-Dir: 247 ± 9 rad s^{-2}; Dir: 286 ± 8 rad s^{-2}).

Our results also show that the level of muscle activation significantly decreased PAV and PLA in any force direction and for either sex ($p < 0.014$, Table 4). Greater muscle activation significantly increased PAA in sagittal flexion ($p = 0.003$) and decreased PAA in lateral flexion ($p < 0.0001$). However, PAA did not change significantly with an increase in muscle activation in sagittal extension.

The time delay between PLA and PAA or PAV did not significantly change based on sex. However, the time delay did significantly decrease for the Non-Directional and Directional warnings compared to the Unwarned condition ($p < 0.0001$, Table 5). Further, the time delay was shorter for Directional warnings compared to Non-Directional warnings. There was no significant interaction between sex and warning type (Directional and Non-Directional) on PLA, PAA, and PAV in any force direction. That is to say, the effect of the warning was the same on head kinematics regardless of sex.

Involuntary vs. Voluntary Response

65 out of 110 of the startle trials (59%) met the acceptance criteria and were included in the analysis. Since the interaction between sex and warning type was not significant on head kinematics, the statistical comparison between voluntary warnings (Non-Directional and Directional) and involuntary warnings (Startle-long and Startle-short) were performed without gender as a factor. PLA, PAV, and PAA significantly decreased with a Startle-short warning (PAV: 4.4 ± 0.1 rad s^{-1}, PAA: 245 ± 10 rad s^{-2}, PLA: 45.4 ± 1.5 m s^{-2}) compared to Non-Directional warnings (PAV: 5.0 ± 0.2 rad s^{-1}, PAA: 267 ± 11 rad s^{-2}, PLA: 48.5 ± 1.4 m s^{-2}) in sagittal extension ($p < 0.038$,

TABLE 3. EMG activation before and after the applied head impulse.

Dependent variable	Independent variable	Estimated mean (SE)				Test	p Value			
		Sag. Ext.	Sag. Flex.	Lat. Right	Lat. Left		Sag. Ext.	Sag. Flex.	Lat. Right	Lat. Left
$EMG_{(Imp)}$ (%MVC)	*Retraction*									
	Unwarned (U)	0.8 (1.4)	− 0.4 (1.9)	0.2 (2.0)	2.0 (1.9)	FM	0.708	0.137	0.648	0.507
	Female (Beta)	− 1.0 (2.1)	4.8 (2.7)	1.9 (3.0)	− 2.5 (2.7)	NU	**0.001**	**0.001**	**0.001**	**0.001**
	Non-Dir (N)	18.4 (1.3)	20.7 (2.1)	20.7 (1.8)	24.5 (2.0)	DU	**0.001**	**0.001**	**0.001**	**0.001**
	Dir (D)	13.6 (1.2)	17.7 (1.7)	14.3 (1.6)	16.0 (1.6)	ND	**0.001**	0.226	**0.001**	**0.001**
	Rebound									
	Unwarned (U)	0.9 (2.4)	1.1 (1.5)	0.3 (1.8)	1.1 (1.4)	FM	0.778	0.675	0.548	0.708
	Female (Beta)	1.3 (3.5)	− 1.3 (2.2)	1.9 (2.4)	− 0.8 (1.6)	NU	**0.001**	**0.001**	**0.001**	**0.001**
	Non-Dir (N)	26.2 (2.2)	17.1 (1.6)	19.0 (1.8)	23.3 (2.0)	DU	**0.001**	**0.001**	**0.001**	**0.001**
	Dir (D)	15.7 (2.0)	12.0 (1.3)	10.9 (1.7)	11.7 (1.7)	ND	**0.001**	**0.002**	**0.001**	**0.001**
$T_{(Post\text{-}Imp\text{-}Max)}$ (ms)	*Retraction*									
	Unwarned (U)	146.7 (4.5)	132.6 (5.9)	137.6 (6.9)	138.5 (7.8)	FM	0.548	0.519	0.859	0.536
	Female (Beta)	3.7 (4.6)	6.0 (6.7)	2.2 (9.9)	− 10.0 (11.5)	NU	**0.001**	0.086	**0.001**	**0.001**
	Non-Dir (N)	101.1 (5.9)	115.2 (8.8)	115.3 (6.2)	107.2 (7.6)	DU	**0.001**	**0.017**	**0.001**	**0.001**
	Dir (D)	101.2 (5.4)	113.3 (7.3)	112.4 (5.7)	114.6 (6.2)	ND	0.990	0.859	0.695	0.458
	Rebound									
	Unwarned (U)	170.8 (9.3)	168.8 (11.1)	161.0 (9.6)	161.8 (9.6)	FM	0.906	0.548	0.548	0.681
	Female (Beta)	2.0 (13.7)	14.7 (17.9)	− 12.2 (14.7)	8.3 (14.6)	NU	**0.001**	**0.001**	**0.001**	**0.001**
	Non-Dir (N)	121.2 (7.9)	128.5 (7.9)	133.0 (7.3)	112.9 (8.8)	DU	**0.001**	**0.001**	**0.001**	**0.001**
	Dir (D)	123.1 (7.2)	132.8 (6.5)	128.5 (6.9)	120.5 (7.1)	ND	0.838	0.681	0.615	0.510
$EMG_{(Post\text{-}Imp\text{-}Max)}$ (%MVC)	*Retraction*									
	Unwarned (U)	59.5 (4.3)	52.4 (6.0)	49.5 (4.6)	53.7 (6.4)	FM	0.806	0.806	0.510	0.519
	Female (Beta)	− 2.2 (6.9)	3.2 (9.7)	− 6.6 (7.1)	6.4 (7.1)	NU	0.086	**0.002**	**0.001**	0.774
	Non-Dir (N)	65.0 (2.8)	66.2 (4.1)	63.1 (3.2)	57.3 (9.2)	DU	**0.031**	**0.007**	0.474	0.586
	Dir (D)	53.5 (2.5)	62.4 (3.4)	52.5 (2.9)	48.2 (7.4)	ND	**0.001**	0.498	**0.001**	0.436
	Rebound									
	Unwarned (U)	58.8 (7.1)	27.6 (2.8)	35.8 (4.1)	46.3 (4.1)	FM	0.954	0.642	0.774	0.097
	Female (Beta)	0.8 (11.6)	− 2.8 (4.2)	2.3 (5.9)	− 12.1 (6.3)	NU	**0.001**	**0.001**	**0.002**	**0.001**

TABLE 3. continued

Dependent variable	Independent variable	Estimated mean (SE)				Test	*p* Value			
		Sag. Ext.	Sag. Flex.	Lat. Right	Lat. Left		Sag. Ext.	Sag. Flex.	Lat. Right	Lat. Left
	Non-Dir (N)	72.9 (3.9)	41.6 (2.8)	48.3 (3.7)	62.4 (3.7)	DU	0.404	0.246	0.906	0.767
	Dir (D)	54.7 (3.5)	30.9 (2.3)	36.3 (3.5)	45.0 (3.0)	ND	**0.001**	**0.001**	**0.001**	**0.001**

Muscle activation just before the impulse, $EMG_{(Imp)}$, and maximum muscle activation time and amplitude, $T_{(Post\text{-}Imp\text{-}Max)}$ and $EMG_{(Post\text{-}Imp\text{-}Max)}$ after the applied impulse are grouped in retraction and rebound muscle groups. Unwarned, Non-Directional (Non-Dir), and Directional (Dir) are presented with their respective estimated means (standard error). The Female (beta) row indicates the amount of change in the respective value compared to male participants for all warning types. Column "Test" indicates the performed statistical test between the two groups in the linear mixed model. F, M, N, D, and U indicates female, male, Non-Directional, Directional, and Unwarned, respectively. As an example, the *p* value = 0.723 in Sag. Ext. indicates that the − 1.1 (2.1) difference between female and male participants was not significant.. *p* values reported are adjusted *p* values. Significant values (p value < 0.05) are bolded.

Table 6). Startle-long warnings only significantly increased PAV in lateral flexion ($p = 0.015$) and was not significant in any other direction compared to the Non-Directional condition.

DISCUSSION

Pre-impact EMG Activation Due To Warning

Female participants exhibited significantly faster muscle onset, $T_{(Pre\text{-}Onset)}$, compared to males. Choice and single reaction time have been previously investigated between male and female participants, and prior research suggests that female participants are faster in auditory reaction time and males are faster in response to a visual stimulus.[25,45] However, there are studies with opposing views that have reported males are faster than females,[21,51] or there was no significant difference between male and female participants.[1,22] Also, it has been suggested that athletes have significantly faster reaction time than more sedentary participants.[15,21,22,38,50] There was no significant difference between males and females in the peak muscle activation due to acoustic warning, and both male and female participants showed faster and less intense muscle activity when given a Directional warning compared to a Non-Directional warning, as suggested in Ref. 19.

Imp and Post-Imp EMG Activation

$EMG_{(Imp)}$ was not significantly different between males and females, which means they both use the same strategy of contracting superficial cervical muscles to prepare themselves before an impending applied force. Also, the time to peak muscle activation and the peak amplitude were not significantly different between males and females. Researchers have reported that the peak muscle activation amplitude due to impact is significantly higher for females compared to males.[3,32,48] However, in all of these studies, female participants demonstrated almost half of the neck strength during MVC trials compared to male participants. In this study, the strength differences between sexes were only in the sagittal direction and not lateral, and the difference in sagittal direction was much lower than mentioned in previous studies. The absence of $EMG_{(Post\text{-}Imp\text{-}Max)}$ differences between sexes may indicate that female participants needed the same muscle activity level to generate the same resistance as male participants to compensate for the applied force. Also, $T_{(Post\text{-}Imp\text{-}Max)}$ did not significantly change by sex. Alsalaheen *et al.*[3] reported that there were no significant differences with sex in muscle onset after a sagittal extension head impulse. $T_{(Post\text{-}Imp\text{-}Max)}$ was significantly shorter when given a Directional or Non-Directional acoustic warning, supporting the previous studies.[5,14,17,19,44] The greater increase in $EMG_{(Post\text{-}Imp\text{-}Max)}$ from a Non-Directional warning compared to a Directional warning or no warning (Unwarned) also supports the findings from some previous studies,[2,19] but contradicts others.[32,48] We attribute the contradiction with the latter studies to differences in administration of the trials. In those studies, no acclimation trials were performed. This may have resulted in a "startle response" in the first warned trials and habituation in the second unwarned trials.[7,43]

Head Kinematics

When comparing genders, head kinematics were significantly greater for female participants compared to male participants. PAV for female participants increased by 22, 25, and 16% in sagittal extension,

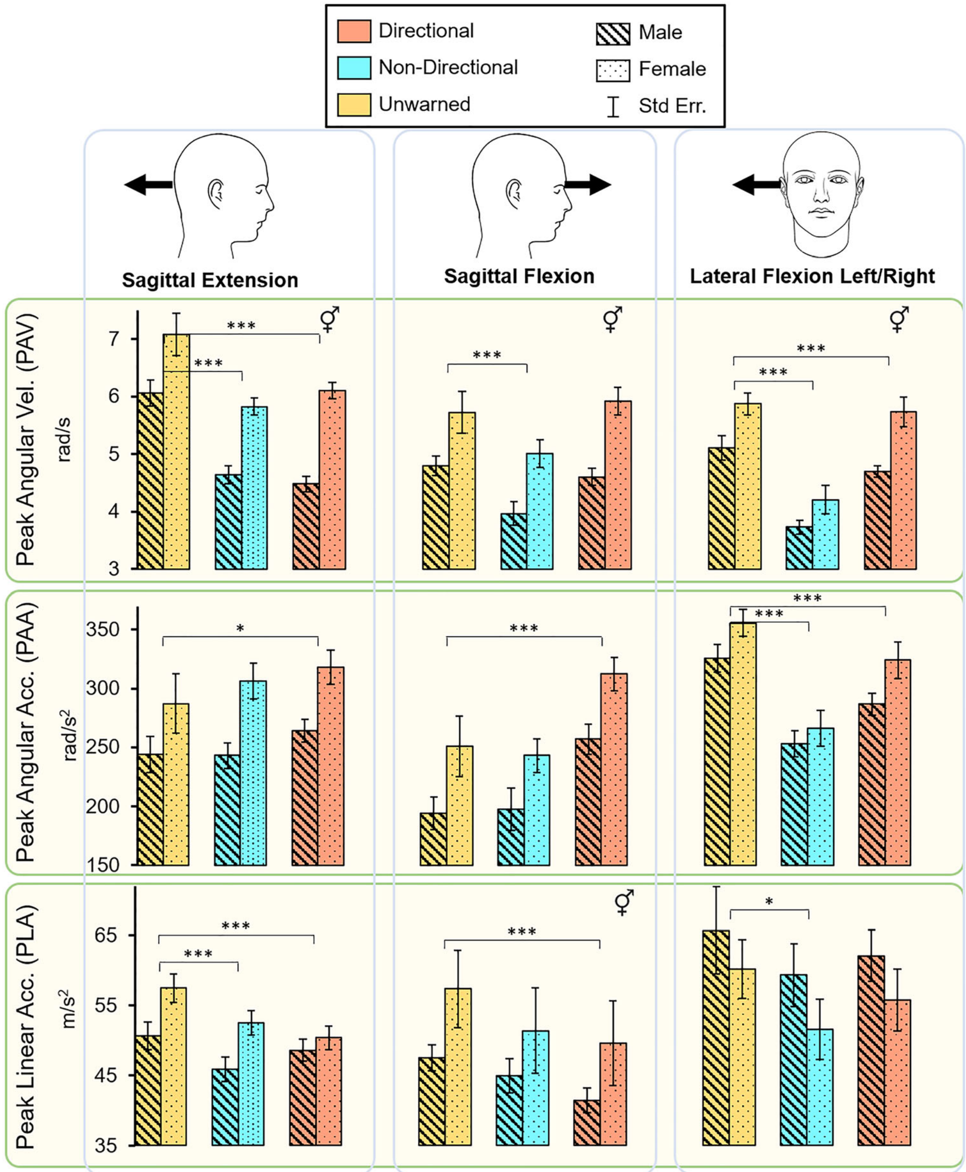

FIGURE 3. Peak angular velocity (PAV), peak angular acceleration (PAA), and peak linear acceleration (PLA) changes based on the sex, warning type, and the three force directions, sagittal extension (Sag. Ext.), sagittal flexion (Sag. Flex.), and coronal lateral flexion (Lat. Flex.). ⚥ Significance between sex, *Significance ($p < 0.032$), ***Significance ($p < 0.0003$)

sagittal flexion, and lateral flexion, respectively, regardless of preparation type. In sagittal extension, Alsalaheen *et al.*[3] did not find significant differences in PAV between sexes, despite large differences between the means (M: 330 vs. F: 194 deg/s). PAA for female participants increased by 22, 24, and 9% in sagittal extension, sagittal flexion, and lateral flexion, respectively. These results are consistent with the general findings found in previous literature in sagittal extension when heading a soccer ball[8] or applied forces in sagittal extension.[32,48] Unlike the differences observed for PAV and PAA, changes in PLA were not consistent and significant for all directions between sexes. PLA only significantly increased by 15% in sagittal flexion for females. This aligns with the laboratory studies that could not find any significant differences between sexes in PLA; However, PLA has been shown to increase by 10% in female participants when heading a soccer ball.[8,46] We tested if there were any sex differences in the time delay between PLA and either PAV or PAA, and found none. However, the time delay was significantly dependent on the type of warning for both genders. Higher risk of sport-related concussion has been reported for female participants and athletes compared to male.[3,8,32,41,46,47] We measured higher kinematic response to the same impact for

TABLE 4. Changes in PAV, PAA, PLA columns, with respect to $EMG_{(Pre\_Imp)}$ and sex.

		PAV (rad/s)		PAA (rad/s^2)		PLA (m/s^2)	
Side	Variable	Beta (SE)	*p* value	Beta (SE)	*p* value	Beta (SE)	*p* value
Sag Ext	Control	5.55 (0.23)		251.5 (15.6)		49.71 (1.60)	
	Female (Beta)	**1.26 (0.39)**	0.0012	53.3 (26.0)	0.0417	4.57 (2.59)	0.0782
	$EMG_{(Imp)}$ (%MVC)	**− 0.05 (0.00)**	< 0.0001	0.0 (0.4)	0.9144	**− 0.18 (0.05)**	0.0003
Sag Flex	Control	4.71 (0.18)		212.7 (14.1)		46.21 (2.26)	
	Female (Beta)	**1.11 (0.29)**	0.0001	35.2 (23.3)	0.1325	**9.00 (3.57)**	0.0123
	$EMG_{(Imp)}$ (%MVC)	**− 0.01 (0.00)**	0.0007	**0.9 (0.3)**	0.0026	**− 0.22 (0.07)**	0.0016
Lat	Control	5.15 (0.17)		310.5 (9.1)		64.45 (4.43)	
Flex	Female (Beta)	**0.68 (0.28)**	0.0177	24.2 (14.8)	0.1032	− 5.43 (7.42)	0.4648
	$EMG_{(Imp)}$ (%MVC)	**− 0.04 (0.00)**	< 0.0001	**− 1.8 (0.3)**	< 0.0001	**− 0.24 (0.10)**	0.0132

The control rows show the mean kinematic value with zero neck muscle activation, $EMG_{(Imp)}$, for males. The Female (beta) row indicates the amount of change in the respective value compared to male participants (intercept) regardless of warning types.$EMG_{(Imp)}$ rows show the coefficient of changes for every %MVC change compared to the associated control row. As an example, the − 0.05 (0.003) value for $EMG_{(Imp)}$ in sagittal extension (Sag. Ext.) shows that for every %MVC increase in muscle activation, the mean PAV, 5.55 rad s^{-1}, decreased − 0.05 for male participants.
Significant values (*p* value < 0.032) are bolded.

TABLE 5. Time delay between PLA and PAV or PAA based on warning and sex.

		PAV (rad/s)		PAA (rad/s^2)	
Side	Type	Mean (SE)	*p* value	Mean (SE)	*p* value
Sag. Ext.	Unwarned	49.3 (2.1)		17.7 (1.1)	
	Female (Beta)	2.9 (3.3)	0.3764	1.4 (1.5)	0.3518
	Non-Dir	**25.9 (1.4)**	< 0.0001	**8.9 (1.1)**	<0.0001
	Dir	**17.9 (1.2)**	< 0.0001	**0.6 (0.9)**	< 0.0001
Sag. Flex.	Unwarned	38.5 (1.9)		15.4 (1.7)	
	Female (Beta)	− 3.8 (2.9)	0.1967	− 3.2 (1.8)	0.0755
	Non-Dir	**23.1 (1.4)**	< 0.0001	**6.9 (2.3)**	0.0002
	Dir	**20.4 (1.2)**	< 0.0001	**1.6 (2.1)**	< 0.0001
Lat.	Unwarned	38.8 (0.9)		19.0 (0.7)	
Flex.	Female (beta)	0.7 (0.9)	0.4385	0.4 (0.9)	0.6621
	Non-Dir	**26.2 (1.2)**	< 0.0001	**12.1 (0.7)**	< 0.0001
	Dir	**19.3 (1.0)**	< 0.0001	**5.1 (0.6)**	< 0.0001

The Unwarned condition shows the time delay for male participants, while the Female (beta) row indicates the change in delay time compared to the male participants for all warning types. Force directions include sagittal extension (Sag. Ext.), sagittal flextion (Sag. Flex.), and lateral flexion (Lat. Flex). Warning types were Non-Directional (Non-Dir), Directional (Dir), and Unwarned. All Directional and Non-Directional warnings were significantly different from each other for all head kinematics and all force directions (*p* value < 0.0001).
Significant values (*p* value < 0.0348) are bolded.

the female participants in subconcussive forces, which may contribute to the higher risk of sport-related concussion in concussive level impact.

In the presence of preparation, PAV and PLA were attenuated by 17 and 11% on average in all force directions with any type of voluntary preparation. The PAA was attenuated by 18% in the lateral plane with either Directional and Non-Directional warnings, but it increased by 7.5 and 29% in sagittal extension and sagittal flexion with Directional warnings. These results are supportive of our previous study.[19] However, Tierney *et al*.[48] reported a significant reduction in PAA for the male participant when they knew about the incoming force but not female participants in the sagittal plane. We tested our results to check for interaction between sex and preparation type in PLA, PAA, and PAV, and there were no significant interaction terms between them. Homayounpour *et al*.[18] concluded that the level of muscle activation would significantly decrease PLA and PAV. We tested this hypothesis again and found that muscle activation significantly decreases the PLA and PAV in all force directions and regardless of sex. Although we measured higher head kinematics, we did not measure any significant differences between males and females in muscle activation magnitude at the beginning of the impulsive force.

TABLE 6. Changes in head kinematics after different warnings.

Side	Variable	PAV (rad/s)		PAA (rad/s^2)		PLA (m/s^2)	
		Mean (SE)	*p* value	Mean (SE)	*p* value	Mean (SE)	*p* value
Sag Ext	Non-Dir	5.01 (0.22)		266.7 (10.6)		48.5 (1.4)	
	Startle Long	5.03 (0.26)	0.9416	246.9 (16.8)	0.2404	48.0 (2.5)	0.8210
	Startle Short	**4.45 (0.15)**	0.0004	**244.9 (9.9)**	0.0300	**45.4 (1.5)**	0.0377
Sag Flex	Non-Dir	4.33 (0.20)		225.0 (9.7)		47.1 (2.5)	
	Startle Long	4.34 (0.27)	0.9507	205.4 (18.6)	0.2957	41.2 (4.0)	0.1426
	Startle Short	4.59 (0.24)	0.2858	235.7 (17.4)	0.5423	53.3 (3.7)	0.1042
Lat	Non-Dir	3.88 (0.17)		258.7 (8.2)		56.1 (4.6)	
Flex	Startle Long	**4.42 (0.22)**	0.0147	287.7 (16.4)	0.0804	64.3 (8.4)	0.3294
	Startle Short	3.73 (0.20)	0.4321	280.5 (15.5)	0.1619	45.9 (7.8)	0.1939

The Non-Directional (Non-Dir) intensity was 75 dB with a 1000 ms warning prior to the head impulse. The Startle-long intensity was 115 dB with a 1000 ms warning prior to the head impulse. The Startle-short intensity was 115 dB with a 420 ms warning prior to the head impulse. PAV, PAA and PLA mean (standard error) are reported for each force direction and warning type.
Significant values (p value < 0.05) are bolded.

Since the muscle activation characteristics were not significant, we hypothesized that anthropometric data may explain the observed differences in kinematics between genders. Specifically, male participants in this study were taller, heavier (not significant), and had greater neck circumference. Also, male participants were stronger in the sagittal plane but not in the lateral plane compared to female participants. We tested if neck strength opposing the applied force is a significant factor in head kinematics, and it was not significant. These results were in line with other studies,[28,32,35,41,46] however, other studies suggested a significant correlation.[10,16] We also tested if neck circumference is a significant factor in head kinematics and it was significant in all directions and for PLA, PAA, and PAV.

To further test this hypothesis, we ran three separate models for each kinematic output with three sets of independent variables: First, sex and warning; Second, neck circumference and warning; and Third, neck strength opposed the direction of pull and warning (Online Table 8). Results showed that sex was significant in 6 out of 9 kinematic responses in three different directions while neck circumference was significant in 7 out of 9 models. Also, neck circumference resulted in significantly better fits compared to sex in most of the models. However, it should be noted that neck circumference was highly correlated to sex and with the males having a larger circumference than females and no overlap in the distribution of measured circumferences for both genders. Neck strength was not a significant factor in predicting head kinematics in any of the force directions.

We measured reduction in PLA and PAV in all directions and PAA just in the lateral direction by providing the participant with Directional or Non-Directional warnings before the applied force. Non-Directional warnings significantly attenuated PAV and PAA more compared to the Directional warnings for applied force in sagittal flexion and lateral flexion. These findings suggest that a warning system or training the players to improve awareness before an impact may reduce head kinematics and consequently the sport-related concussion risk.[3,12,19,34,41] However, the effect of muscle activation in higher forces is still questionable.[24]

Involuntary vs. Voluntary Response

Since the startling response is faster and more intense compared to the voluntary response,[19] we hypothesized this involuntary response could help with kinematic attenuation. Our results show that PAV, PAA, and PLA significantly decreased in sagittal extension in Startle-Short trials compared to Non-Directional trials. The sagittal extension results are supported by previous research that compared the results with the Unwarned condition in a sled study.[30] Our results also align with results that showed a significant reduction in PAA and PLA between Unwarned vs. startle conditions, but they did not significantly differ between low-intensity vs. high-intensity acoustic warnings.[31]

Although reaction time was significantly lower in startle trials than Non-Directional warnings, there was no benefit in kinematics comparing Non-Directional to Startle-Long conditions when the startling stimulus was played 1000 ms before the applied force. Also, head kinematics only attenuated in startle-short trials compared to Non-Directional conditions in sagittal extension force direction. Since only 59% of our startle trials produced a measured startle in the laboratory setup with the 115 dB sound without any background noise, this approach may not be ideal to guarantee muscle activation within the startle time period.

However, it can be used as an alternative method when there is not enough time to send the voluntary warning before an impact.

Study Limitations and Future Directions

This study had limitations. We only tested sub-concussive forces since it is not ethical to test living subjects with concussive force levels, and it is not possible to test cadavers when muscle activation and preparation are involved. This study may help to inform simulation studies considering muscle activation. As a result, the complete dataset including applied forces, muscle activation, and head kinematics is available online. Although the instrumented mouthguard data have been validated,[9] there could be errors associated with the data,[42] but these mouthguards are widely used in field studies for players. Further, the conclusions and relationships evaluated in this study are likely unchanged even if these errors exist. During the MVC trials, although participants were asked not to use their abdominal muscles and were strapped to the chair to isolate neck muscles, abdominal muscle activity was observed during the MVC trials as explained by Ref. 3. Dataset: https://bit.ly/3xFWWyd.

The results of this study may be incorporated into sport-related concussion studies in the future that investigate the efficacy of instrumented head protection. There are challenges that need to be addressed, such as the presence of high environmental noises, that may impact the utility of this methodology. The utilization of noise-canceling earbuds may create a large enough decibel differential that the proposed methodology would still be effective, but that condition would need to be tested to verify plausibility.

Sex differences in head kinematics and muscle activation were investigated in response to different warning types: Directional, Non-Directional, Startle-long, and Startle-short. We found that neck circumference, which has been shown to correlate with measures of body size and level of sexual dimorphism,[49] best explained the difference in head kinematics between sexes despite similar muscle activation levels. Consequently, neck circumference could provide insights into injury risk. Also, our results show that preparation before an impending impact decreases peak linear acceleration and peak angular velocity regardless of sex. More studies are warranted to explore the role of sexual dimorphism and differences in injury potential from head impacts during sports. Additional work measuring the muscle activation level and timing in deeper cervical muscles is warranted to better understand these sex differences and implications on injury risk.

SUPPLEMENTARY INFORMATION

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