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ABSTRACT

Purpose: Sports related concussion (SRC) is a risk for players involved in high impact, collision sports. A history of SRC is a risk factor for future concussions, but the mechanisms underlying this are unknown. Despite evidence that most visible signs and symptoms associated with sports concussion resolve within 7-10 days, it has been proposed that subclinical loss of neuromuscular control and impaired motor functioning may persist and be associated with further injury. Alternatively, indicators of poor sensorimotor performance could be independent risk factors. This study investigated if a history of SRC and/or pre-season sensorimotor performance predicted season head/neck injuries. **Methods:** 190 male rugby league, rugby union and Australian Football League players participated. Pre-season assessments included self-report of SRC within the previous 12 months and a suite of measures of sensorimotor function (balance, vestibular function, cervical proprioception and trunk muscle function). Head/neck injury data were collected in the playing season. **Results:** Forty-seven players (25%) reported a history of SRC. A history of concussion was related to changes in size and contraction of trunk muscles. Twenty-two (11.6%) players sustained a head/neck injury during the playing season, of which, 14 (63.6%) players had a previous history of SRC. Predictors of in-season head/neck injuries included history of SRC, trunk muscle function and cervical proprioceptive errors. Five risk factors were identified and players with three or more of these had 14 times greater risk of sustaining a season neck/head injury (sensitivity of 75% and specificity of 82.5%) than players with 2 or fewer risk factors. **Conclusion:** The modifiable risk factors identified could be used to screen football players in the pre-season and guide development of exercise programs aimed at injury reduction. **Key Words**: risk factors; proprioception; trunk muscles; football; rugby

INTRODUCTION

Sport related concussion (SRC) is a common sports injury worldwide, with an estimated 1.6 to 3.8 million individuals hospitalized annually in the USA (22). Players who do not report SRC and do not seek medical care are estimated to be 2-10 times greater in number (24). Injuries during sport account for approximately 20% of all traumatic brain injury (TBI) cases requiring hospitalization (22). In Australia, hospital separation data from 2002/3 to 2010/11 demonstrated a 60.5% (95% CI 41.7 - 77.3) increase in hospitalizations due to SRC that could only partly be explained by increases in sports participation. After adjustment for participation, rates were highest for motor sports, equestrian activities, Australian football, rugby and roller sports (8). In the USA sporting context, the number of SRCs reported to the National Collegiate Athletic Association increased significantly by 7% annually from the 1988/9 to 2003/4 academic years (18). The increasing trends in concussion incidence may reflect increasing awareness of SRC, changes in player risk, changes in treatment strategies or changes in data collection methodology (21).

Concussions sustained during participation in sport place a significant burden on society. This includes increased burden on both the systems responsible for providing safe medical care of athletes and the health care systems needed to assess and treat the injured players. There is also an associated burden placed on the individuals themselves and their families. The short- and long-term consequences of concussion may mean that potentially years of productive life are lost, resulting in substantial economic costs for individuals, families and society. Because of these factors, it is critical to identify and mitigate any potentially modifiable risk factors associated with this injury.

One of the known risk factors for SRC, is a history of previous concussion. This was first described by Gerberich et al (9) in a study of American high school football injuries. This finding has been noted across a range of sports (1). A recent systematic review of risk factors for SRC noted level 1 evidence with a high degree of certainty for a history of previous SRC with estimates ranging from 3-6 fold increased risk of future SRC (1). Although the mechanisms underlying the increased injury risk post-concussion are not known, one of the proposed mechanisms is that loss of neuromuscular control and resultant impaired motor functioning could persist following sports concussion and be associated with future injury risk (5). While most adult athletes are thought to exhibit full clinical recovery of symptoms by 10 days, there is emerging evidence suggesting that abnormalities in brain and motor functioning can persist well beyond the typical time course of recovery (29).

Efficient neuromuscular control and co-ordination of movement is reliant on input from sensory systems. Sensorimotor function includes individual and collective abilities of the physiological systems involved reception of sensory stimuli, transmission and processing of central nervous system signals and conversion of signals to allow motor output. Elements of sensorimotor function, which can be measured and are indicative of specific sensorimotor function, include neurocognitive processing ability, neuromuscular control and co-ordination and regulation of postural control (37). Proprioception is thought to be important for normal movement, rehabilitation and prevention of injuries (31). Sensory information from neck proprioceptive receptors is processed in tandem with information from the vestibular system, a system which also affects control of deeper trunk muscles via the lateral vestibulo-spinal tract (10). There are extensive anatomical connections between neck proprioceptive receptors and vestibular inputs (36), which together with vision, control posture and balance. Further, a recent prospective study showed that in the acute phase following SRC, elite rugby union and league players exhibited alterations of both balance strategy and motor control of trunk muscles (11). Altered motor control of trunk muscles has been shown to be predictive of head/ neck injuries in Australian football players (12), however other measures of sensorimotor function and possible relationships with player history of SRC were not investigated.

The aims of this study were to investigate if: a) a history of previous SRC and pre-season sensorimotor function were related; and b) if history of SRC and or sensorimotor function predict future head/neck injury risk in rugby league, Australian football and rugby union players.

METHODS

Players were recruited from the three main codes of football played in Australia (rugby league, Australian football and rugby union). All players provided written informed consent (including parental consent for players under 18 years) and the study was approved by the Australian Catholic University Ethics Committee. Assessments were conducted during the pre-season, including questionnaires (to ascertain self-reported history of SRC in the last 12 months and demographic information) and a suite of sensorimotor assessments. Injury information was recorded by the clubs' medical staff during the playing season.

<u>Pre-season sensorimotor system testing</u>. A suite of tests of sensorimotor function used in a previous study of professional rugby union and rugby league players was used (11). Measures of balance, vestibular system function, cervical spine proprioception (joint position sense) and trunk

muscle size/function were conducted at club facilities using portable equipment prior to commencement of the playing season.

Balance Assessment. Each participant completed the Stability Evaluation Test (SET) (VSR Sport Portable Balance System, Natus Medical Incorporated, San Carlos, CA 94070 USA). Postural stability was assessed, with eyes closed, under varying base of support conditions. The protocol implemented has been shown to have moderate to good reliability (ICC = 0.75-0.93) (39). The protocol included six stance conditions (20s each) without footwear **or socks**: feet together, single leg stance (standing on non-dominant leg) and tandem stance (non-dominant foot behind) on firm, then foam, surfaces.

Vestibular system function testing. Assessment of oculo-motor and vestibulo-ocular reflex (VOR) function was performed to identify signs of central or peripheral vestibular system function deficits. The video head impulse test (vHIT) (EyeSeeCam Interacoustics AS) was used to record overt and covert saccadic movement with VOR gain (milliseconds, ms) and left-right Asymmetry (%) recorded (26). Vestibular ocular reflex (VOR) gain represents eye movement relative to head movement as an expression of the horizontal VOR. The vHIT software automatically calculates the gain for impulses applied by an assessor in the horizontal plane at 40 ms, 60 ms and 80 ms and identifies any asymmetry between left and right responses (40). The range of normal responses for impulses at 60 ms is 0.65 to 1.17 and 80 ms is 0.76 to 1.18 (26). Recent data suggests that a gain near 1 and less than 8% asymmetry is consistent for healthy adults aged up to 70 years (40).

Cervical proprioception. To measure cervical proprioception, a modified joint position sense test using neck torsion (trunk movement with stationary head), rather than head rotation, was used to differentiate cervical from vestibular deficits (7). A laser was attached to the mid-sternum, with the beam projecting onto a target 90 cm from the chest. Participants were blindfolded and seated with their feet and buttocks positioned on soft foam to minimize proprioceptive cues. The examiner held the participant's head in the neutral position and participants crossed their arms, held away from the body. The participant rotated their trunk and returned to their perceived neutral position, and the laser beam position was marked on the target. The test was conducted 6 times alternately to each side (35). Cervical proprioception error was calculated using the mean of absolute errors (AE) for the 6 left and 6 right trials. The difference between the start and returning position of the laser beam on the target was measured in degrees using the formula, angle = $\tan^{-1}$(error distance/ 90) (32). The 12 measures were averaged to give an overall mean score (sensitivity = 78%, ICC = 0.68) (32).

Trunk muscle imaging. Ultrasound imaging and magnetic resonance imaging (MRI) were used to image trunk muscles. The protocols have been published in full elsewhere (14, 15). Ultrasound imaging was conducted using LOGIQ e apparatus with a 5 MHz curvilinear transducer (GE Healthcare, Wuxi, China). The multifidus muscles were imaged bilaterally from the L2 to L5 vertebral levels (14), and the quadratus lumborum muscles were imaged bilaterally in line with the L3-4 vertebral interspace (15). The transversus abdominis, internal oblique and multifidus muscles were imaged at rest and on contraction. For MRI, participants were screened by a medical practitioner prior to imaging. They were positioned in supine lying and transverse images were captured from the top of the lumbar spine to the level of the second sacral vertebra using a Siemens 3 Tesla Magnetom Verio MR system (Siemens, Erlangen, Germany). Two T2 weighted sequences of the lumbar spine paravertebral musculature (repetition time = 4660 ms, echo time = 87 ms, flip angle = 120°, field of view 260 mm, and number of averages = 1) were employed to maximize clarity and definition of the fascial borders. The first T2 sequence was from T12 to S2 in the axial plane parallel to the patient's body. The second T2 sequence was from L3 to S2 parallel to the L4/5 disc to best assess the multifidus muscle. Ultrasound and magnetic resonance images were stored and measured offline using OsiriX medical imaging software (Geneva, Switzerland). Researchers with demonstrated reliability conducted the measurements of quadratus lumborum size (ICC = 0.99) (15), multifidus muscle size (ICC mean L2-L5 = 0.94) (14), multifidus muscle thickness (ICC = 0.88-0.95, relaxed and contracted) (38) and abdominal muscle thickness (transversus abdominis ICC = 0.62-0.98; internal oblique ICC = 0.69-0.99, relaxed and contracted) (13).

Season head/neck injury data. Injury data, collected by the medical club during the season, were provided to the research team at the end of the playing season. A head/neck 'injury' was defined as a physical condition related to playing or training for football that prevented a player from completing a game or playing in subsequent games. Head/neck injuries were diagnosed and recorded by medical staff, using the standardized process documented by the Australian Football League, and included concussion, facial fractures, neck sprains and 'other 'head and neck injuries (27). Injury during the playing season was coded as either ''head/neck injury'' or ''no head/neck injury.'' The "no head/neck injury" group included players with no injury and those with any other (non-head/neck) injury in the playing season.

Statistical Analysis. SPSS version 22.0 [IBM, USA] was used for analyses. The measurements tested as predictive factors included both categorical and continuous variables (age, height, mass, history of concussion in the last 12 months, and sensorimotor function including balance, vestibular system function, cervical proprioception and trunk muscle size and contraction measures). All predictive factors were assessed against both history of SRC (injury or no injury) and head/neck injury in the subsequent playing season (injury or no injury). Univariate associations between categorical variables were examined using chi-square tests. Continuous variables of age, height, mass, and sensorimotor function including balance variables, were analyzed using independent samples t-tests with the between groups factor being either of the injury variables. One-factor repeated measures analysis of variance (ANOVA) was conducted to compare the continuous predictive variables (vestibular system function, cervical proprioception and trunk muscle size and contraction measures) between groups (injury/no injury) with side (right/left) as a within subjects factor. If a significant relationship existed, Receiver Operating Characteristic (ROC) curves were used to determine an optimal cut-point for each continuous variable in predicting the injury outcome variables. The optimal cut-point was obtained as the point where the true positive rate (sensitivity) was maximized and the false positive rate (1-specificity) was minimized i.e. the point closest to the top of the y-axis. The cut-points were then used to convert the continuous variables to a binary form. The sensitivity and specificity of each measure and the unadjusted odds ratio for predicting history of SRC and head/neck injury in the playing season were estimated from cross-tabulations. If there was a significant association between history of SRC and head/neck injury in the playing season, all variables significantly associated with the former were tested as mediators or moderators in the relationship. Firstly, correlations between the continuous measures and the 2 injury variables were assessed. If a continuous measurement was correlated with both injury variables, a logistic regression model to predict head/neck injury in the playing season using a history of SRC as a covariate was compared against a model that included only the binary form of the continuous measure. Variables would be considered a moderator if there was a significant interaction with history of SRC or a mediator if there was no interaction but the variable was an independent predictor, which reduced the effect of history of SRC. Finally, potential binary predictors were then entered into logistic regression models in order of their univariate effect (P value) for predicting history of SRC and for predicting head/neck injury in the playing season. A forward sequential method was used to conserve statistical power and to investigate possible collinearity between variables at each step. To avoid the possibility of type II errors, variables were retained in the model if $P<0.1$ (19). Because this was an exploratory study, no adjustments for multiple comparisons were made, also in order to avoid type II errors (3). Variables that were not significant multivariate predictors or that were collinear with other variables were dropped from the model.

RESULTS

A total of 190 male football players participated in the study. Mean (SD) participant age (years), height (cm) and mass (kg) were: rugby league (n=20): 23.8 (3.6) years, 184 (6.6) cm, 100 (9.4) kg; Australian football (n=113): 23.8 (4.3) years, 189 (7.8) cm, 89 (9.6) kg; and rugby union (n=57): 19.6 (4.6) years, 185 (7.0) cm, 95.2 (13.0) kg. Twenty-seven players were left foot dominant (14%). There were some differences between players from different codes with Australian football players being taller and lighter and rugby union players being younger than players from the other codes ($p < 0.01$).

Number of previous sports related concussions and in season head/neck injuries

Of the 190 players, 47 (25%) reported a previous SRC within the previous 12 months. A total of 22 (11.7%) players sustained a head/neck injury in the playing season. Of these, 16 were SRCs, and the remaining 6 injuries included 3 facial fractures and 3 'other' head/neck injuries defined according to the categories used in the AFL injury surveillance report (27). Of the 22 players who sustained a head/neck injury, 14 players (63.6%) reported a history of SRC within the previous 12 months.

Previous history of sports concussion and sensorimotor function

Self-reported history of SRC was not related to abnormalities of balance, vestibular system function and cervical proprioception at baseline (see Table, Supplemental Digital Content 1, Relationship between self-reported history of sports-related concussion and sensorimotor function, http://links.lww.com/MSS/A994). However, there was a relationship with muscle CSA in that players with a history of SRC had smaller multifidus muscles at all four of the vertebral levels measured (L2: P=0.004; L3: P=0.002; L4: P<0.001 and L5: P=0.032) vertebral levels and larger quadratus lumborum muscles (P=0.003) (Table 1). There was also a relationship between history of SRC and muscle contraction of the multifidus and anterolateral abdominal wall muscles (transversus abdominis and internal oblique muscles). Players with history of SRC contracted their multifidus muscles at the L2/3 vertebral level more than players without a history of SRC (P=0.043). They also contracted their transversus abdominis (P=0.007) and internal oblique (P=0.005) muscles more on the right side than the left compared with players without a history of SRC (Table 1).

In season head/neck injury and pre-season sensorimotor function

Season head/neck injury was related to trunk muscle size (Table 2), trunk muscle contraction (Table 3) and cervical proprioception (Table 2). Players with head/neck injury had smaller multifidus muscles at all four vertebral levels measured (L2: P=0.008; L3: P=0.004; L4: P=0.009 and L5: P=0.09), and larger quadratus lumborum muscles (P=0.016). Notably, the size of the quadratus lumborum muscles at the L3-4 vertebral level was larger than the multifidus muscles at the L5 vertebral level for players with a season head/neck injury (Table 2). Players who sustained a season head/neck injury contracted their multifidus muscles more at the L2/3 (P=0.09) and more asymmetrically at the L4/5 (P=0.029) vertebral level, with greater contraction on the left side, than players who did not sustain an injury (Table 3). For the anterolateral abdominal muscles, a similar pattern of increased contraction was seen especially on the right side for the transversus abdominis muscle (P=0.09). Results for cervical proprioception (Table 2) showed that players who sustained a head neck injury in the playing season had increased joint position error when rotating the trunk to the left side (P=0.044), with 9 of 22 (41%) of players who later sustained a head/neck injury demonstrating joint position error greater than 4.5 degrees for this test. Results for balance testing using the SET showed that players who went on to have a head/neck injury were not significantly different from players who did not have an in-season injury for and of the six conditions tested (P>0.10). Results for vestibular function were also not significantly different between injured and non-injured players (P>0.10). Complete results for all measures are presented in Table, Supplemental Digital Content 2, Relationship between head/neck injury in the playing season and pre-season sensorimotor function, http://links.lww.com/MSS/A995).

Predictors of in season head/neck injury

Measures with a significant area under the curve (AUC) are shown in Table 4. The measures with the highest sensitivity were CSA and contraction of the multifidus muscle and cervical joint position error. The measures with the highest specificity included asymmetry of the contraction of the transversus abdominis muscle, size of the quadratus lumborum and multifidus muscles and cervical joint position error. The unadjusted and adjusted odd ratios for the factors associated with previous history of SRC are shown in Table 5, and for the predictors of season head/neck injury in Table 6. The adjusted odds ratios in Table 6 indicate that if a player has one or more of the measures listed, for example a history of concussion plus one or more of a small multifidus (< 5.7 cm^2 at L3; P=0.017), increased cervical joint position error (> 0.6 degrees error on trunk rotation to the left; P=0.003), asymmetrical contraction of the transversus abdominis muscle (> 0.7 mm more on the right side than the left side; P=0.09) or a large quadratus lumborum muscle (> 10.1 cm^2; P=0.06), their odds of a head/neck injury during the season would be significantly increased. Of the 174 players who provided all measurements, 132 possessed 2 or less risk factors, while 42 possessed 3 or more risk factors. Only 3.8% of players with 2 or fewer risk factors had a head/neck injury compared to 35.7% of players with 3 or more risk factors (P < 0.0001) with an odds-ratio of 14.1 (95% CI 4.7, 42.1). This suggests that the odds of a player with three or more of risk factors having a head/neck injury is 14 times higher than that of a player with 2 or fewer risk factors. Using the criterion of 3 or more risk variables results in a sensitivity of 75% and specificity of 82.5% for predicting head/neck injuries.

Factors that were significant predictors were tested for mediating or moderating effects with previous SRC in increasing the risk of season head/neck injury. No variables were moderators but contraction of the transversus abdominis muscle was a mediator in the risk of future head/neck injury in that it was related to previous injury and also increased the risk of future injury (P=0.07).

DISCUSSION

Previous history of concussion and sensorimotor function

A history of SRC was related to several aspects of sensorimotor function. Players with a history of SRC had increased odds of having altered size and contraction of their trunk muscles, namely smaller multifidus (OR=3.8 95% CI 1.6-9.0), larger quadratus lumborum muscles (OR=3.0 95% CI 1.3-6.9), and asymmetrical (increased) contraction of their transversus abdominis muscles (OR=3.0 95% CI 1.3-7.0). A similar result was seen for the internal oblique muscle, with an asymmetrical (increased) contraction, although this was only significant at the univariate level. Of the tests of sensorimotor function conducted, the only mediator of future head/neck injuries in the playing season was motor control of the transversus abdominis muscle. This is the deepest of the anterolateral abdominal muscles and it plays an important role in spinal control. It is controlled independently of the other abdominal muscles, affects intra-abdominal pressure (17) and tensions the thoracolumbar fascia (2). Players with a history of SRC contracted their transversus abdominis muscles significantly more on the right side. This pattern differs from that of healthy individuals, where the transversus abdominis muscle has been shown to be symmetrical at rest and on contraction (23). In the acute phase post SRC, rugby union and league players were also previously shown to have increased thickness of anterolateral abdominal muscles on the right side (11). It was proposed that this could represent splinting or over-holding, possibly leading to increased trunk stiffness in association with an acute injury. As contraction of the transversus abdominis muscle was found to be a mediator of future head/neck injuries, it is possible that alterations in motor control of this muscle do not completely resolve following SRC, and could contribute to an increased risk of future head/neck injuries in players with a history of SRC.

Predictors of in season head/neck injury

The results of the current investigation are consistent with results of a recent systematic review of risk factors for SRC which reported that athletes with a history of SRC were at higher risk of sustaining another concussion (1). The odds ratio reported in the current investigation is within the range of estimates ranging from a 3-6 fold increased risk of future SRC reported by Abrahams et al (1).

Three of the 5 predictors of head/neck injury identified in the current investigation were related to trunk muscle function. Efficient neuromuscular control and co-ordination of movement is reliant on input from sensory systems, and muscle spindles are considered the most important source of proprioception (30). Spinal muscles such as the lumbar multifidus are known to have a high concentration of muscle spindles, and play an important sensory role, as well as a biomechanical role controlling segmental motion and the lordosis of the lumbar spine (4). In contact sports, a high proportion of head/neck injuries occur when tackling (6). The position of the trunk at the time of impact is crucial (34). Before the impact of a tackle, the player recruits their muscles from the feet up in preparation for impact. Players are taught to place their lead foot forwards, and to drive into the tackle, whilst looking up with a strong, solid spine. During impact, the forces on the player cause deformation of the bodies coming in to contact and the forces propagate through the tackler's body from the shoulder/neck (point of contact) through the body and back to the ground (34). Correct foot placement and optimal positioning of the trunk and head are recognized as important elements of safe tackling techniques, to minimize the risk of injury (33). In support of the importance of the role of the multifidus muscles, a recent study showed that an inability to contract the lumbar multifidus muscles predicted occurrence of head/neck injuries in Australian football players (12). With respect to lower limb injuries in Australian football players, it has been proposed previously that when the lumbar multifidus muscles are insufficient, inadequate control of the lumbo-pelvic region and poor force transfer may be a possible mechanism of injury. Inability to adequately control spinal motion in the sagittal plane may result in recruitment of the quadratus lumborum muscles in an attempt to compensate (15). Increased bilateral recruitment of the quadratus lumborum muscles would restrict lateral flexion of the lumbar spine. It is recommended in the guidelines for tackling that efficient and safe tackling techniques involve sufficient lateral flexion of the trunk to allow the player to bring the head to the side and away from the tackle contact (33). It is therefore possible that poor trunk proprioception and control of the position of the lumbar spine in the sagittal plane, combined with restriction of trunk lateral flexion could increase the risk of head/neck injury in physical collisions and tackles.

An alteration in proprioception of the cervical spine, with greater repositioning error when players rotated the trunk to the left side, also significantly increased the odds of sustaining a head/neck injury. For trunk rotation to the left side, a mean of 4.5 (1.7) degrees joint position error was reported. The value of 4.5 degrees using head relocation, rather than the trunk relocation used here, in any direction has previously been suggested to represent abnormal cervical proprioception in those with neck pain and neck related dizziness (20). During tackling with the dominant side, it is important that players can laterally flex and rotate the head to the side and away from the tackle contact (34). If players were unable to position themselves well and pre-set the head in an optimal position prior to contact (28), this could explain the increased risk of head/neck injuries associated with altered cervical proprioception. An interesting finding of the current investigation was that altered proprioception was an independent predictor of in-season head/neck injuries regardless of the history of SRC. A previous investigation reported that cervical proprioception was impaired in rugby union players (28), so it may be that exposure to the repeated impacts associated with contact sport could adversely affect the sensitivity of the receptors located in cervical muscles and joints. This effect on proprioception could impede the ability to move the head away from the tackle contact, thus predisposing the player to head/neck injuries.

A history of SRC or was not related to results of testing of the vestibular system or balance. Pre-season testing of these systems also did not predict in-season head/neck injuries. With respect to the vHIT, it is possible that changes of the VOR as indicated by the vHIT may reflect more severe SRCs, which occur less commonly or may have recovered by the time of assessment. With respect to balance, the results of the current investigation are consistent with results of a recent investigation of collegiate athletes which also found that those with a self-reported history of concussion did not have poorer static or dynamic balance than matched controls (25). A limitation of the current investigation is that an increased risk of injury post-SRC could be associated with other sensorimotor systems not assessed in the current investigation, such as persistent alterations in neurocognition. Other limitations are that history of previous SRC relied on player self-report, the accuracy of which may have been influenced by recall and willingness to report previous concussions, and the diagnostic certainty of self-report SRC is unknown.

The clinical application of our findings is that the results provided could be used to screen players at risk of in-season head/neck injuries. Players with 3 or more of the **5** identified risk factors had 14 times higher odds of injury than players with 2 or fewer risk factors, with a sensitivity of 75% and specificity of 82.5%. The three factors with the highest adjusted odds ratios were a self-reported history of SRC, decreased size of the multifidus muscle and increased cervical joint position error. Size of trunk muscles and proprioception of the cervical spine can both be assessed in clinical practice and are modifiable (16, 31). The clinical cut-offs provided could be used to screen players in the pre-season, to identify players most likely to have an injury. Targeted intervention programs could then be based on the identified deficits. The results suggest that pre-season training aimed at injury reduction could include exercises to improve motor control of the trunk and proprioception of the cervical spine.

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Supplemental Digital Content 1. Word document—Relationship between self-reported history of sports-related concussion and sensorimotor function

Supplemental Digital Content 2. Word document—Relationship between head/neck injury in the playing season and pre-season sensorimotor function

Table 1. Measurements of trunk muscle size and function for those with and without a self-reported history of sports concussion within the last 12 months.

Muscle	N	No concussion in the 12 months prior to testing		Concussion in the 12 months prior to testing		P value
		Right	Left	Right	Left	
Cross-sectional area, cm^2						
MF L2 CSA average	173	4.0 (0.9)		3.5 (0.9)		**0.004**
MF L3 CSA average	175	7.0 (1.9)		5.9 (1.9)		**0.002**
MF L4 CSA average	175	10.3 (2.2)		8.9 (2.2)		**< 0.001**
MF L5 CSA average	175	10.8 (1.7)		10.1 (1.7)		**0.032**
QL CSA average	175	9.2 (2.0)		10.4 (2.3)		**0.003**
Relax and contraction, mm						
MF L2/3 rest[a]	186	23.6 (4.5)	24.0 (4.0)	25.0 (4.5)	25.5 (4.0)	0.20
MF L2/3 contraction[b]		1.8 (1.8)	2.0 (1.6)	2.5 (1.8)	2.2 (1.6)	0.13
% Change		7.6%	8.3%	10.0%	8.6%	
Average contraction		*1.9 (1.4)*		*2.4 (1.4)*		***0.043***
MF L3/4 rest[a]	186	27.0 (4.5)	27.0 (4.2)	28.0 (4.5)	28.6 (4.2)	**0.07**
MF L3/4 contraction[b]		1.9 (2.0)	2 (1.7)	2.5 (2.0)	2.4 (1.7)	0.90
% Change		7.0%	7.4%	8.9%	8.4%	
Average contraction		*1.9 (1.5)*		*2.4 (1.5)*		***0.05***
TrA rest[a]	186	4.2 (1.2)	4 (1.1)	4.3 (1.2)	4.4 (1.1)	**0.07**
TrA contraction[b]		1.9 (1.2)	2 (1.1)	2.3 (1.2)	1.7 (1.1)	0.90
% Change		45.2%	50.0%	53.5%	38.6%	
Average contraction		*1.9 (0.9)*		*2.1 (1)*		*0.23*
IO rest[a]	186	12.4 (2.9)	12.0 (2.7)	12.4 (2.9)	12.0 (2.7)	0.14
IO contraction[b]		1.8 (1.8)	2.0 (1.7)	2.4 (1.8)	1.8 (1.7)	**0.007**
% Change		14.5%	16.7%	19.4%	15.0%	
Average contraction		1.9 (1.5)		2.1 (1.5)		0.41

Values are reported as the estimated marginal means (EMM) and sd.
[a] Relaxed muscle thickness; [b] Difference in muscle thickness between the contracted and relaxed condition; % change refers to the percentage change in muscle thickness between the relaxed and contracted condition. CSA = cross-sectional area; MF – Multifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; L4/5- L4/5 zygapophyseal joint; L5/S1-L5/S1 zygapophyseal joint.

Table 2. Joint position error and trunk muscle size for players who did and did not sustain a head/neck injury in the playing season.

Variable	N	No head/neck injury during playing season		Head/neck injury during playing season		P value
		Right	Left	Right	Left	
Cervical proprioception test						
Joint position error, degrees	190	3.92 (1.8)	3.74 (1.7)	3.58 (1.8)	4.52 (1.7)	**0.044**
Cross-sectional Area, cm²						
MF L2 CSA *average*	174	*4.0 (0.9)*		*3.4 (0.9)*		***0.008***
MF L3 CSA a*verage*	176	*6.9 (1.9)*		*5.5 (1.9)*		***0.004***
MF L4 CSA a*verage*	176	*10.1 (2.2)*		*8.8 (2.2)*		***0.009***
MF L5 CSA a*verage*	176	*10.7 (1.7)*		*10.0 (1.7)*		***0.09***
QL CSA *average*	175	*9.4 (2.1)*		*10.6 (2.1)*		***0.016***

Values are reported as the estimated marginal means (EMM) and sd. MF – Multifidus muscle; QL – Quadratus lumborum muscle.

Table 3. Measurements of trunk muscle size and function for players who did and did not sustain a head/neck injury in the playing season.

Muscle	N	No head/neck injury during playing season		Head/neck injury during playing season		P value
		Right	Left	Right	Left	
Relax and contraction, mm						
MF L2/3 rest[a]	186	23.8 (4.5)	23.9 (4.0)	25.3 (4.5)	25.4 (4.0)	0.96
MF L2/3 contraction[b]		1.9 (1.9)	2.0 (1.6)	2.5 (1.9)	2.5 (1.6)	0.84
% Change		7.9%	8.3%	9.8%	9.8%	
Average contraction		*1.9 (1.4)*		*2.5 (1.4)*		**0.09**
MF L3/4 rest[a]	186	27.0 (4.5)	26.8 (4.2)	29.0 (4.5)	29.4 (4.2)	0.43
MF L3/4 contraction[b]		2.0 (2.0)	1.9 (1.7)	2.3 (2.0)	2.8 (1.7)	0.29
% Change		7.6%	7.2%	8.0%	9.4%	
Average contraction		*2.0 (1.5)*		*2.5 (1.5)*		*0.11*
MF L4/5 rest[a]	186	31.3 (4.8)	31.2 (4.9)	33.7 (4.8)	33.5 (4.9)	0.87
MF L4/5 contraction[b]		2.7 (1.9)	2.7 (2.0)	2.4 (1.9)	3.3 (2.0)	**0.029**
% Change		8.8%	8.7%	7.0%	9.9%	
Average contraction		*2.7 (1.7)*		*2.9 (1.7)*		*0.77*
MF L5/S1 rest[a]	186	32.26 (5.2)	32.28 (5.2)	34.91 (5.2)	35.72 (5.2)	0.19
MF L5/S1 contraction[b]		2.8 (2.0)	3.0 (2.3)	2.7 (2.0)	2.9 (2.3)	0.83
% Change		8.7%	9.4%	7.8%	8.0%	
Average contraction		*2.9 (2.0)*		*2.8 (2.0)*		*0.77*
TrA rest[a]	186	4.2 (1.2)	4.1 (1.1)	4.6 (1.2)	4.5 (1.1)	0.62
TrA contraction[b]		2.0 (1.2)	1.8 (1.1)	2.4 (1.2)	1.8 (1.1)	**0.09**
% Change		47.0%	44.3%	52.5%	40.9%	
Average contraction		*1.9 (1.0)*		*2.12 (1.0)*		*0.32*
IO rest[a]	186	12.4 (2.9)	11.3 (2.6)	12.9 (2.9)	12.7 (2.6)	0.17
IO contraction[b]		1.9 (1.8)	1.9 (1.7)	2.3 (1.8)	2.6 (1.7)	0.49
% Change		15.3%	16.4%	18.0%	20.5%	
Average contraction		*1.9 (1.5)*		*2.5 (1.5)*		*0.11*

Values are reported as the estimated marginal means (EMM) and sd.
[a] Relaxed muscle thickness; [b] Difference in muscle thickness between the contracted and relaxed condition; % change refers to the percentage change in muscle thickness between the relaxed and contracted condition. MF - Multifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; L4/5- L4/5 zygapophyseal joint; L5/S1-L5/S1 zygapophyseal joint.

Table 4. ROC curves optimal cut values for variables associated with either self-reported history of concussion or head/neck injury during the season.

Measure	AUC	95% confidence interval	P value	Optimal risk cut-point	Sensitivity	Specificity
History of concussion						
Age, years	0.63	(0.53, 0.73)	0.007	< 21.5	63.8%	61.0%
Height, cm	0.60	(0.51, 0.68)	0.039	< 186	59.6%	61.0%
MF L2 CSA average, cm^2	0.65	(0.56, 0.75)	0.004	< 3.8	71.8%	57.4%
MF L3 CSA average, cm^2	0.69	(0.59, 0.79)	< 0.001	< 6.2	71.8%	64.7%
MF L4 CSA average, cm^2	0.69	(0.59, 0.79)	< 0.001	< 8.8	69.2%	64.7%
MF L5 CSA average, cm^2	0.61	(0.51, 0.72)	0.030	< 10.6	68.4%	56.3%
QL CSA average, cm^2	0.61	(0.51, 0.72)	0.030	> 10.1	48.7%	73.3%
TrA contraction interaction, mm	0.64	(0.54, 0.73)	0.006	> 0.1	46.7%	76.6%
IO contraction interaction, mm	0.63	(0.53, 0.72)	0.050	> 0.5	62.2%	56.0%
Head/neck injury during the season						
MF L2 CSA Average, cm^2	0.68	(0.54, 0.80)	0.015	< 3.7	65.0%	59.7%
MF L3 CSA Average, cm^2	0.70	(0.58, 0.83)	0.003	< 5.7	65.0%	69.9%
MF L4 CSA Average, cm^2	0.67	(0.55, 0.80)	0.012	< 9.5	70.0%	60.3%
MF L5 CSA Average, cm^2	0.62	(0.49, 0.76)	0.07	< 10.1	60.0%	66.0%
QL CSA Average, cm^2	0.65	(0.51, 0.78)	0.032	> 10.1	55.0%	71.0%
MF L4/5 contraction interaction, mm	0.62	(0.50, 0.75)	0.06	< 0.1	68.2%	53.0%
TrA contraction interaction, mm	0.63	(0.52, 0.75)	0.041	> 0.8	54.5%	74.4%
Joint Position Error interaction, degrees	0.66	(0.53, 0.78)	0.018	< -0.6	63.6%	66.7%

MF - Multifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; QL – Quadratus Lumborum muscle.

Table 5. Unadjusted and adjusted odds ratios for age, height, multifidus and quadratus lumborum muscle size and contraction of the transversus abdominis and internal oblique muscles as associated with history of concussion within the previous 12 months.

Measure	%"non-risk" group with concussion history	%"risk" group with concussion history	Unadjusted odds ratio	P value	Adjusted odds ratio (95% CI)	P value
MF L3 CSA Average < 6.2, cm^2	11.1%	36.8%	4.7 (2.1, 10.2)	< 0.001	3.8 (1.6, 9.0)	0.002
MF L4 CSA Average < 8.8, cm^2	12.0%	36.0%	4.1 (1.9, 8.9)	< 0.001		
MF L5 CSA Average < 10.6, cm^2	12.4%	32.6%	3.4 (1.6, 7.4)	0.002		
TrA contraction > 0.1 interaction, mm	18.2%	38.9%	2.9 (1.4, 5.8)	0.004	3.0 (1.3, 7.0)	0.009
Age < 21.5, years	16.5%	35.3%	2.8 (1.4, 5.5)	0.004	2.6 (1.1, 6.2)	0.028
MF L2 CSA Average < 3.8, cm^2	13.6%	30.6%	2.8 (1.3, 6.0)	0.010		
QL CSA Average > 10.1, cm^2	16.8%	34.5%	2.6 (1.3, 5.4)	0.011	3.0 (1.3, 6.9)	0.011
Height < 186, cm	18.1%	33.7%	2.3 (1.2, 4.5)	0.018	2.1 (0.9, 4.8)	0.09
IO contraction > 0.5 interaction, mm	17.7%	31.1%	2.1 (1.1, 4.2)	0.040		

MF - Multifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; QL – Quadratus Lumborum muscle.

Table 6. Unadjusted and adjusted odds ratios for history of concussion in the last 12 months, multifidus and quadratus lumborum muscle size, joint position error and contraction of the multifidus muscle as predictors of head/neck injury.

Measure	%"non-risk" group with head/neck injury in season	%"risk" group with head/neck injury in season	Un-adjusted odds ratio	P value	Adjusted odds ratio (95% CI)	P value
Concussion in the previous 12 months	5.7%	29.8%	7.1 (2.7, 18.2)	< 0.001	4.5 (1.5, 13.8)	0.009
MF L3 CSA Average < 5.7, cm^2	6.0%	21.7%	4.3 (1.6, 11.5)	0.005	4.1 (1.3, 13.0)	0.017
Joint Position Error interaction < -0.6,degrees	6.7%	20.0%	3.5 (1.4, 8.8)	0.009	5.7 (1.8, 18.2)	0.003
TrA contraction interaction > 0.8, mm	7.6%	22.2%	3.5 (1.4, 8.7)	0.010	2.5 (0.9, 7.5)	0.09
MF L4 CSA Average < 9.5, cm^2	6.0%	18.4%	3.5 (1.3, 9.7)	0.015		
QL CSA Average > 10.1, cm^2	7.6%	19.6%	3.0 (1.2, 7.7)	0.039	2.9 (1.0, 8.8)	0.06
MF L5 CSA Average < 10.1 cm^2	7.2%	18.5%	2.9 (1.1, 7.6)	0.028		
MF L2 CSA Average < 3.7, cm^2	7.1%	17.3%	2.8 (1.0 , 7.3)	0.05		
MF L4/5 contraction interaction < 0.1, mm	7.4%	16.3%	2.4 (0.9, 6.2)	0.07		

MF - Multifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; QL – Quadratus Lumborum muscle.

APPENDIX 1

Table 1. Relationship between self-reported history of sports-related concussion and sensorimotor function

Variable	N	No concussion in the 12 months prior to testing	Concussion in the 12 months prior to testing	P value
Demographics				
Age, years	188	22.9 (4.6)	21.0 (4.7)	**0.017**
Height, cm	188	188 (7.9)	185 (7.3)	**0.045**
Mass, kg	188	91 (11.3)	93 (11.9)	0.39
Stability evaluation Test, degrees/second				
Firm – Feet together	187	0.8 (0.2)	0.7 (0.2)	0.16
Firm – Single leg	187	2.0 (0.7)	2.1 (1.0)	0.69
Firm – Tandem	187	1.8 (1.2)	1.6 (1.0)	0.31
Foam – Feet together	187	2.1 (0.7)	2.1 (0.6)	0.82
Foam – Single leg	187	4.8 (1.6)	4.9 (1.8)	0.49
Foam – Tandem	187	5.1 (2.9)	5.3 (2.9)	0.81

Variable	N	No concussion in the 12 months prior to testing		Concussion in the 12 months prior to testing		P value
		Right	Left	Right	Left	
Muscle cross-sectional area, cm^2						
MF L2 CSA	173	4.0 (1.0)	4.0 (1.0)	3.5 (0.9)	3.5 (0.9)	0.28
Average		4.0 (0.9)		3.5 (0.9)		**0.004**
MF L3 CSA	175	7.0 (2.0)	7.0 (1.9)	6.0 (2.0)	5.7 (1.9)	0.16
Average		7.0 (1.9)		5.9 (1.9)		**0.002**
MF L4 CSA	175	10.3 (2.2)	10 (2.2)	8.8 (2.2)	8.9 (2.2)	0.91
Average		10.3 (2.2)		8.9 (2.2)		**< 0.001**
MF L5 CSA	175	10.8 (1.8)	11 (1.7)	10.1 (1.8)	10.1 (1.7)	0.86
Average		10.8 (1.7)		10.1 (1.7)		**0.032**
QL CSA	174	9.1 (2)	9 (2.4)	10 (2)	10.6 (2.4)	0.15
Average		9.3 (2.1)		10.3 (2.1)		**0.007**

Muscle relax and contraction, mm						
MF L2/3 rest[a]		23.6 (4.5)	24.0 (4.0)	25.0 (4.5)	25.5 (4.0)	0.20
MF L2/3 contraction[b]	186	1.8 (1.8)	2.0 (1.6)	2.5 (1.8)	2.2 (1.6)	0.13
% Change		7.6%	8.3%	10.0%	8.6%	
Average contraction		*1.9 (1.4)*		*2.4 (1.4)*		***0.043***
MF L3/4 rest[a]		27.0 (4.5)	27.0 (4.2)	28.0 (4.5)	28.6 (4.2)	**0.07**
MF L3/4 contraction[b]	186	1.9 (2.0)	2 (1.7)	2.5 (2.0)	2.4 (1.7)	0.90
% Change		7.0%	7.4%	8.9%	8.4%	
Average contraction		*1.9 (1.5)*		*2.4 (1.5)*		***0.05***
MF L4/5 rest[a]		30.9 (4.7)	31 (4.8)	33.8 (4.7)	33.5 (4.8)	0.41
MF L4/5 contraction[b]	186	2.6 (1.9)	3 (2.0)	2.9 (1.9)	3 (2.0)	0.78
% Change		8.4%	9.7%	8.6%	9.0%	
Average contraction		2.7 (1.7)		2.9 (1.7)		0.38
MF L5/S1 rest[a]		31.9 (5.1)	32 (5.2)	34.7 (5.1)	34.8 (5.2)	0.89
MF L5/S1 contraction[b]	186	2.7 (2.0)	3 (2.3)	3.1 (2.0)	3.2 (2.3)	0.50
% Change		8.5%	9.4%	8.9%	9.2%	
Average contraction		2.8 (1.9)		3.2 (1.9)		0.33
TrA rest[a]		4.2 (1.2)	4 (1.1)	4.3 (1.2)	4.4 (1.1)	0.14
TrA contraction[b]	186	1.9 (1.2)	2 (1.1)	2.3 (1.2)	1.7 (1.1)	**0.007**
% Change		45.2%	50.0%	53.5%	38.6%	
Average contraction		1.9 (1.0)		2 (1.0)		0.54
IO rest[a]		12.4 (2.9)	12.0 (2.7)	12.4 (2.9)	12.0 (2.7)	0.23
IO contraction[b]	186	1.8 (1.8)	2.0 (1.7)	2.4 (1.8)	1.8 (1.7)	**0.005**
% Change		14.5%	16.7%	19.4%	15.0%	
Average contraction		1.9 (1.5)		2.1 (1.5)		0.41
Cervical proprioception test						
Joint position error, degrees	188	3.7 (1.8)	3.8 (1.8)	4.3 (1.7)	4.0 (1.7)	0.40
		3.8 (1.3)		4.1 (1.2)		0.13

Vestibular function (vHIT)						
60 ms	188	1 (0.1)	0.96 (0.1)	0.99 (0.1)	0.96 (0.1)	0.40
		0.98 (0.1)		0.98 (0.1)		0.82
80 ms	188	0.93 (0.1)	0.92 (0.2)	0.94 (0.1)	0.95 (0.2)	0.51
		0.93 (0.1)		0.95 (0.1)		0.36

Values are reported as the estimated marginal means (EMM) and sd.
CSA = cross-sectional area
[a] Relaxed muscle thickness; [b] Difference in muscle thickness between the contracted and relaxed condition; % change refers to the percentage change in muscle thickness between the relaxed and contracted condition. MF - Mutlifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; L4/5- L4/5 zygapophyseal joint; L5/S1-L5/S1 zygapophyseal joint.

Table 2. Relationship between head/neck injury in the playing season and pre-season sensorimotor function

Variable	N	No head/neck injury during the playing season	Head/neck injury during the playing season	P value
Demographics				
Age, years	190	22.3 (4.6)	23.7 (5.5)	0.20
Height, cm	190	187.4 (7.9)	186.5 (6.2)	0.62
Mass, kg	190	91.3 (11.5)	95.4 (10.7)	0.11
Stability evaluation Test, degrees/second				
Firm – Feet together	189	0.8 (0.2)	0.7 (0.2)	0.60
Firm – Single leg	189	2.0 (0.8)	2.2 (1.2)	0.31
Firm – Tandem	189	1.8 (1.2)	1.6 (1.2)	0.56
Foam – Feet together	189	2.2 (0.7)	2.1 (0.6)	0.58
Foam – Single leg	189	4.7 (1.6)	5.1 (1.7)	0.41
Foam – Tandem	189	5.2 (2.8)	4.6 (3.1)	0.35

Variable	N	No head/neck injury during the playing season		Head/neck injury during the playing season		P value
		Right	Left	Right	Left	
Muscle cross-sectional area, cm^2						
MF L2 CSA	174	4. 0 (1.0)	4.0 (1.0)	3.3 (1.0)	3.4 (1.0)	0.23
Average		4.0 (0.9)		3.4 (0.9)		**0.008**
MF L3 CSA	176	6.9 (2.0)	6.8 (2.0)	5.6 (2.0)	5.5 (2.0)	0.87
Average		6.9 (1.9)		5.5 (1.9)		**0.004**
MF L4 CSA	176	10.1 (2.2)	10.2 (2.3)	8.6 (2.2)	8.9 (2.3)	0.22
Average		10.1 (2.2)		8.8 (2.2)		**0.009**
MF L5 CSA	176	10.7 (1.8)	10.7 (1.7)	9.9 (1.8)	10.2 (1.7)	0.11
Average		10.7 (1.7)		10.0 (1.7)		**0.09**
QL CSA	175	9.2 (2.0)	9.5 (2.4)	10.1 (2)	11.0 (2.4)	0.10
Average		9.4 (2.1)		10.6 (2.1)		**0.016**

Muscle relax and contraction, mm						
MF L2/3 rest[a]		23.8 (4.5)	23.9 (4.0)	25.3 (4.5)	25.4 (4.0)	0.96
MF L2/3 contraction[b]	186	1.9 (1.9)	2.0 (1.6)	2.5 (1.9)	2.5 (1.6)	0.84
% Change		7.9%	8.3%	9.8%	9.8%	
Average contraction		1.9 (1.4)		2.5 (1.4)		**0.09**
MF L3/4 rest[a]		27.0 (4.5)	26.8 (4.2)	29.0 (4.5)	29.4 (4.2)	0.43
MF L3/4 contraction[b]	186	2.0 (2.0)	1.9 (1.7)	2.3 (2.0)	2.8 (1.7)	0.29
% Change		7.6%	7.2%	8.0%	9.4%	
Average contraction		2.0 (1.5)		2.5 (1.5)		0.11
MF L4/5 rest[a]		31.3 (4.8)	31.2 (4.9)	33.7 (4.8)	33.5 (4.9)	0.87
MF L4/5 contraction[b]	186	2.7 (1.9)	2.7 (2.0)	2.4 (1.9)	3.3 (2.0)	**0.029**
% Change		8.8%	8.7%	7.0%	9.9%	
Average contraction		2.7 (1.7)		2.9 (1.7)		0.77
MF L5/S1 rest[a]		32.26 (5.2)	32.28 (5.2)	34.91 (5.2)	35.72 (5.2)	0.19
MF L5/S1 contraction[b]	186	2.8 (2.0)	3.0 (2.3)	2.7 (2.0)	2.9 (2.3)	0.83
% Change		8.7%	9.4%	7.8%	8.0%	
Average contraction		2.9 (2.0)		2.8 (2.0)		0.77
TrA rest[a]		4.2 (1.2)	4.1 (1.1)	4.6 (1.2)	4.5 (1.1)	0.62
TrA contraction[b]	186	2.0 (1.2)	1.8 (1.1)	2.4 (1.2)	1.8 (1.1)	**0.09**
% Change		47.0%	44.3%	52.5%	40.9%	
Average contraction		1.9 (1.0)		2.12 (1.0)		0.32
IO rest[a]		12.4 (2.9)	11.3 (2.6)	12.9 (2.9)	12.7 (2.6)	0.17
IO contraction[b]	186	1.9 (1.8)	1.9 (1.7)	2.3 (1.8)	2.6 (1.7)	0.49
% Change		15.3%	16.4%	18.0%	20.5%	
Average contraction		1.9 (1.5)		2.5 (1.5)		0.11
Cervical proprioception test						
Joint position error, degrees	190	3.92 (1.8)	3.74 (1.7)	3.58 (1.8)	4.52 (1.7)	**0.044**
		3.83 (1.3)		***4.05 (1.3)***		0.45

Vestibular function (vHIT)						
60 ms	190	1 (0.1)	0.96 (0.1)	0.96 (0.1)	0.95 (0.1)	0.28
		0.98 (0.1)		0.95 (0.1)		0.29
80 ms	190	0.94 (0.1)	0.93 (0.2)	0.91 (0.1)	0.93 (0.2)	0.43
		0.94 (0.1)		0.92 (0.1)		0.56

Values are reported as the estimated marginal means (EMM) and sd.
CSA = cross-sectional area
[a] Relaxed muscle thickness; [b] Difference in muscle thickness between the contracted and relaxed condition; % change refers to the percentage change in muscle thickness between the relaxed and contracted condition. MF - Mutlifidus muscle; TrA - Transversus Abdominis muscle; IO - Internal Oblique muscle; L4/5- L4/5 zygapophyseal joint; L5/S1-L5/S1 zygapophyseal joint.