University of Nevada, Reno

Abnormalities in Lower Extremity Muscle Recruitment Following Concussion Using Electromyography and Tandem Gait

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Kinesiology

by

Joseph McCarley, B.S., CES

Dr. Nicholas G. Murray/Thesis Advisor

May 2023

THE GRADUATE SCHOOL

We recommend that the thesis

prepared under our supervision by

Joseph McCarley

entitled

Abnormalities in Lower Extremity Muscle Recruitment Following Concussion Using Electromyography and Tandem Gait

Be accepted in partial fulfillment of the

requirements for the degree of

Master of Science

Nicholas Murray, Ph.D.

Advisor

Nora Constantino, Ph.D.

Committee Member

Alireza Tavakkoli, Ph.D.

Graduate School Representative

Markus Kemmelmeier, Ph.D., Dean

Graduate School

May, 2023

Abstract

Following sports-related concussion (SRC) athletes are 1.9-3.5x more likely to sustain a musculoskeletal (MSK) injury for up to one year following concussion. Surface electromyography(sEMG) can be used to measure abnormal muscle recruitment that may be the cause of the increased injury risk. **Purpose:** To examine abnormalities in lower extremity muscle recruitment between healthy, concussed, and symptom free individuals. **Methods:** 11 healthy NCAA Division I athletes and one University student (8 males, 3 females; Age: 19.5±1.31 years old) were recruited and compared to 9 NCAA Division I athletes (5 males, 4 females; Age: 20.22±1.79 years old. Average days following concussion: 1.11±0.33) of which 5 came back for a follow up symptom free appointment (3 males, 2 females; Age: 19.6±0.89 years old; Average days following concussion: 30.8±29.7). Participants had sEMG sensors (2000 Hz, 1-cm center-to-center distance, 1000 gain, Delsys, Natick, MA) applied to their tibialis anterior (TA), peroneal (PER), and medial gastrocnemius (M. GAST). To start, participants performed three self-paced walking trials (10m), along with three pseudorandomized trials of single task (ST), and three dual task (DT) trials. ST trials involved participants walking heel-to-toe for 3 meters, turning around, and walking back. DT trials have the same walking task with an addition cognitive task. All data was filtered, rectified, and normalized to the self-paced gait trials for analyzation. A series of one-way ANOVAs, Kruksal-Wallis, and RMANOVAs, were used to evaluate for statistical significance between concussion, healthy, and symptom free individuals. **Results:** There was significant differences in the TA turn phase in both ST and DT conditions in the healthy vs symptom free subjects

(CONvSF ST Turn: p=0.03; CONvSF DT Turn: p=0.04). The trend in the data shows a decrease in TA recruitment followed by an increase in PER recruitment in the healthy vs concussion subjects. The concussion vs symptom free subjects shows a consistent pattern of increased TA and M. GAST recruitment, as well as a decrease in PER recruitment.

Conclusion: The trends present in the data point to a decrease in gait velocity as well as an increase in medio-lateral instability following concussion with an observed recovery upon symptom free evaluation. While the symptom free athletes had improved medio-lateral stability, they are still less stable than their healthy counterparts, meaning they are beginning return to play with instability present. This indicates that rehabilitation professionals should consider implementing lower extremity stability exercises in stage I of return to play.

Contents

Tables v
Table 1. v
Table 2. vi
Table 3. vii
Table 4. viii
Table 5. ix
Table 6. x
Table 7. xi
Table 8. xii
Table 9. xiii
Table 10. xiv
Figure 1. xv
Figure 2. xvi
Introduction 1
Concussion 1
Concussion Epidemiology 1
Concussion Pathophysiology 1
Concussion Assessment 2
Background on Concussion Assessment 2
Visual, Vestibular, and Cognitive Assessments 3
Tandem Gait 4
Postural Control 4
Relationship between Concussion and Postural Control 4
Using Tandem Gait to Evaluate Postural Control Following Concussion 5
Surface Electromyography 5
Background on Surface Electromyography 5
Using Surface Electromyography to Evaluate Postural Control 6
Research Purpose 6
Hypothesis 6
Methods 7
Participants 7

Testing Protocol 7
Data Analysis 10
Statistical Analysis 11
Results 12
Discussion 14
References 19

Tables

Table 1. Demographic information of 11 healthy NCAA Division I athletes, as well as one healthy University of Nevada Reno Student, 9 NCAA Division I athletes with concussion, 5 of which came in for a follow up symptom free assessment.

Variable	Healthy	Concussion	Symptom Free
Age	19.5±1.31	20.22±1.79	19.6±0.89
Height (cm)	178.86±8.8	178.65±14.5	182.37±15.7
Weight (kg)	88.36±23.1	85.81±23.2	86.02±22.1
Days Post Con.	N/A	1.11±0.33	30.8±29.7
Num. Cons.	0.17±0.39	2.33±1.66	2.33±1.66
VOMS Change	0±0.29	18±16.9	1±1.79

Notes: Days Post Con= Number of days between concussion and assessment; Num. Cons.= Number of concussions

Table 2. Healthy and concussion % Gait during tandem gait

Task	Muscle	H % GAIT	CON % GAIT	HvCON d
ST	TA	157.5±32.2	123.49±35.1	1.01
	PER	146.68±31.8	152.71±30	0.19
	M. GAST	127.07±23.4	122.27±31.1	0.17
DT	TA	130.68±26.5	98.82±19.1	1.39
	PER	124.24±24.2	123.88±18.5	0.017
	M. GAST	94.15±13.1	96.54±20.9	0.14

Notes: ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; H% GAIT= healthy sEMG during tandem gait, normalized to normal gait; CON%= concussion sEMG during tandem gait, normalized to normal gait; p<0.05

Table 3. Overall healthy and concussion F-stat and p-value during tandem gait.

Task	Muscle	HvCON F-Stat	HvCON p-value
ST	TA	1.42	0.25
	PER	0.39	1.00
	M. GAST	0.02	0.89
DT	TA	1.72	0.21
	PER	0.08	0.67
	M. GAST	0.23	0.64

Notes: $F_{(1,19)}$; ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; $p<0.05$

Table 4. Healthy and concussion % Gait during the three phases of tandem gait.

Phase	Muscle	Task	H % GAIT	CON % GAIT	HvCON d
Pass 1	TA	ST	155.84±44.1	129.8±41.4	0.61
		DT	133.46±25.5	101.88±23.9	1.28
	PER	ST	153.26±44.3	155.89±38.9	0.07
		DT	133.92±35.8	120.6±18.3	0.47
	M. GAST	ST	117.52±27.9	121.62±31.1	0.14
		DT	89.86±19.77	97.81±16.84	0.43
Turn	TA	ST	179.95±60.5	118.37±36.4	1.23
		DT	157.64±42.1	105.3±40.8	1.26
	PER	ST	178.12±62.7	187.97±47.2	0.18
		DT	131.53±41.6	161.85±57	0.61
	M. GAST	ST	146±64.8	126.49±36.5	0.37
		DT	120.37±44.4	105.42±40.4	0.35
Pass 2	TA	ST	149.45±30.8	129.4±51.9	0.47
		DT	129.79±32.4	91.67±20.04	1.42
	PER	ST	133.52±32.8	160.3±64.2	0.53
		DT	108.83±24.7	124.3±22.9	0.65
	M. GAST	ST	129.17±37.3	128.96±33.3	0.01
		DT	91.66±17.4	102.48±22.1	0.54

Notes: ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; H% GAIT= healthy sEMG during tandem gait, normalized to normal gait; CON %GAIT= concussion sEMG during tandem gait, normalized to normal gait; Pass 1= Initial 3-meter walk; Pass 2= 3 meter walk back; Turn= Time between Pass 1 and Pass 2; $p<0.05$

Table 5. Phases of tandem gait of healthy and concussion F-stat and p-value.

Phase	Muscle	Task	HvCON F-Stat	HvCON p-value
Pass 1	TA	ST	1.28	0.27
		DT	1.92	0.29
	PER	ST	0.01	0.91
		DT	0.57	0.46
	M. GAST	ST	0.02	0.82
		DT	0.23	0.55
Turn	TA	ST	3.17	0.09
		DT	3.93	0.06
	PER	ST	0.08	0.67
		DT	0.53	0.48
	M. GAST	ST	0.45	0.51
		DT	0.81	0.38
Pass 2	TA	ST	0.83	0.37
		DT	3.58	0.07
	PER	ST	0.63	1.00
		DT	0.68	0.42
	M. GAST	ST	0.00	0.99
		DT	0.79	0.39

Notes: $F(1,19)$; ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; $p<0.05$

Table 6. Overall concussion and symptom free % Gait during tandem gait

Task	Muscle	CON % GAIT	SF % GAIT	HvSF d
ST	TA	122.78±29.55	145.33±25.07	0.72
	PER	167.32±122.05	139.8±48.37	0.66
	M. GAST	112.92±39.92	130.7±37.42	0.01
DT	TA	98.52±12.84	110.4±27.24	0.57
	PER	126.68±75.65	118.04±60.87	0.56
	M. GAST	91.62±29.87	109.44±29.04	0.27

Notes: ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; CON% GAIT= concussion sEMG during tandem gait, normalized to normal gait; SF %GAIT= symptom free sEMG during tandem gait, normalized to normal gait; $p<0.05$

Table 7. Overall concussion and symptom free F-stat and p-value during tandem gait.

Task	Muscle	CONvSF F-Stat	CONvSF p-value
ST	TA	3.75	0.13
	PER	1.23	0.53
	M. GAST	0.47	0.41
DT	TA	0.42	0.33
	PER	0.85	0.55
	M. GAST	1.13	0.35

Notes: F(1,4); ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; $p<0.05$

Table 8. Concussion and symptom free % Gait during the three phases of tandem gait.

Phase	Muscle	Task	CON % GAIT	SF % GAIT	CON v SF d
Pass 1	TA	ST	124±35.16	139.76±18.72	0.3
		DT	98.32±17.52	104.31±19.6	0.12
	PER	ST	145.44±64.04	121.55±40.21	1.47
		DT	107±42.54	105±49.52	0.82
	M. GAST	ST	105.61±40.36	128.29±46.61	0.23
		DT	87.28±28.34	103.11±31.16	0.28
Turn	TA	ST	107.95±38.32	170.9±20.43	1.23
		DT	89.94±18.07	131.95±35.79	0.75
	PER	ST	190.31±137.3	211.32±66.3	0.29
		DT	185.16±185.69	149.12±58.35	0.27
	M. GAST	ST	113.38±60.31	158.7±42.09	0.54
		DT	103.22±44.88	138.78±48.17	0.75
Pass 2	TA	ST	124.61±22.63	142.28±39.43	0.33
		DT	89.14±21.83	106.91±42.21	0.75
	PER	ST	169.16±148.2	137.59±60.5	0.45
		DT	119.53±67.73	118.13±82.54	0.22
	M. GAST	ST	118.56±34	125±48.7	0.15
		DT	91.22±27.53	106.06±31.52	0.14

Notes: ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; CON% GAIT= concussion sEMG during tandem gait, normalized to normal gait; SF% GAIT= symptom free sEMG during tandem gait, normalized to normal gait; Pass 1= Initial 3-meter walk; Pass 2= 3 meter walk back; Turn= Time between Pass 1 and Pass 2; $p<0.05$; *= significant at $p<0.05$

Table 9. Phase F-stat and p-value for concussion and symptom free individuals.

Phase	Muscle	Task	CONvSF F-Stat	CONvSF p-value
Pass 1	TA	ST	0.95	0.384
		DT	0.45	0.583
	PER	ST	1	0.373
		DT	0.03	0.865
	M. GAST	ST	0.59	0.484
		DT	0.99	0.375
Turn	TA	ST	12.22	*0.025
		DT	8.61	*0.043
	PER	ST	0.15	0.716
		DT	0.28	0.624
	M. GAST	ST	1.63	0.27
		DT	1.41	0.301
Pass 2	TA	ST	2.18	0.214
		DT	1.65	0.268
	PER	ST	0.5	0.518
		DT	0.009	0.929
	M. GAST	ST	0.13	0.739
		DT	0.65	0.467

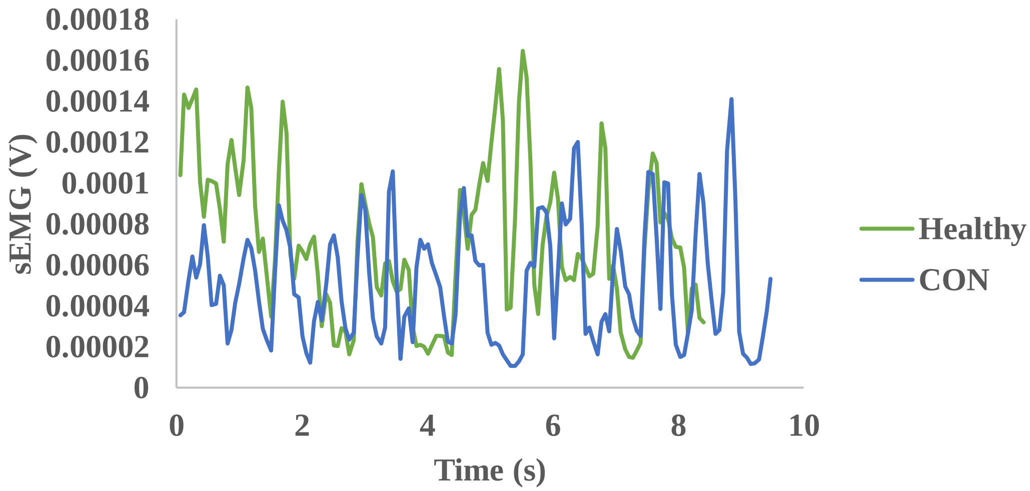
Notes: $F(1,4)$; ST= single-task; DT= dual-task; TA= tibialis anterior; PER= peroneals; M. GAST= medial gastrocnemius; $p<0.05$, *= significant at $p<0.05$

Table 10. Correlations between % GAIT, Time to complete tandem gait, and VOMS change score

Muscle	Condition	Task	Time	VOMS
TA	Healthy	ST	-0.5(0.1)	0.31(0.33)
		DT	-0.5(0.09)	0.15(0.65)
	Concussion	ST	-0.29(0.45)	-0.57(0.11)
		DT	-0.34(0.37)	-0.63(0.07)
	SF	ST	-0.33(0.58)	-0.006(0.99)
		DT	0.73(0.16)	0.32(0.5)
PER	Healthy	ST	-0.15(0.65)	0.22(0.5)
		DT	0.13(0.68)	0.28(0.38)
	Concussion	ST	-0.09(0.82)	-0.42(0.27)
		DT	-0.32(0.41)	-0.41(0.28)
	SF	ST	-0.84(0.07)	0.04(0.96)
		DT	-0.17(0.78)	-0.14(0.82)
M. GAST	Healthy	ST	-0.4(0.2)	-0.22(0.5)
		DT	-0.26(0.41)	-0.27(0.4)
	Concussion	ST	-0.6(0.09)	-0.46(0.21)
		DT	-0.7(0.04)	-0.49(0.19)
	SF	ST	-0.97(0.01)*	-0.07(0.92)
		DT	-0.39(0.52)	-0.12(0.85)

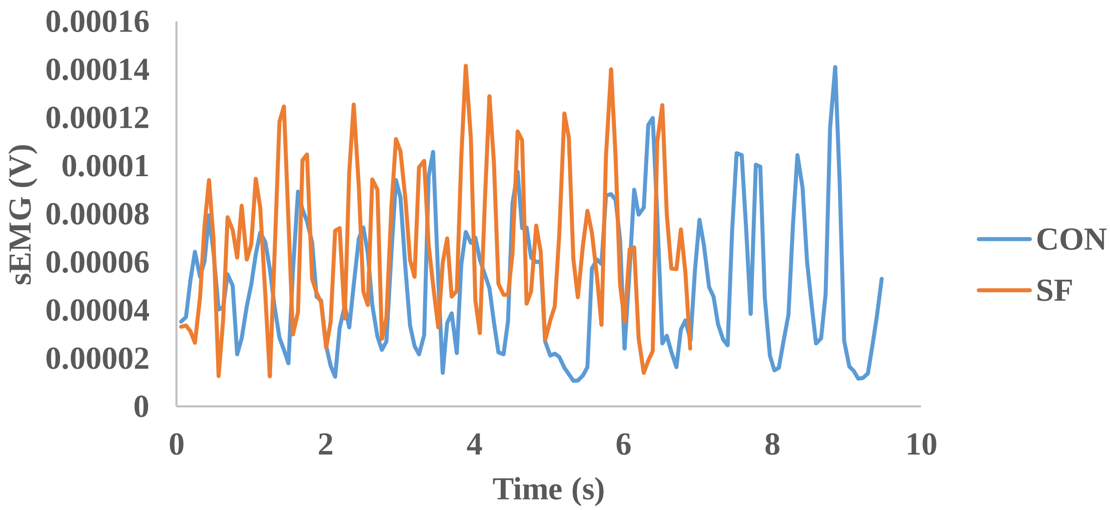
Notes: TA= tibialis anterior; PER= peroneals; MGAST= medial gastrocnemius; ST= single-task; DT= dual task; SF= symptom free; VOMS= vestibular ocular motor screening change score, *= significant at $p<0.05$

Figure 1. Tibialis anterior surface electromyography comparison for healthy and concussion. Following concussion, athletes exhibit lower recruitment of the tibialis anterior during tandem gait.



Notes: (s)= seconds, sEMG= surface electromyography, (V)= volts

Figure 2. Tibialis anterior surface electromyography (sEMG) for consussion and symptom free indidivuals. Following concussion athletes recover anterior tibialis recrtuiment and exhibit significant diffrences in the turning phase of tandem gait (CONvSF ST Turn: p=0.03, CONvSF DT Turn: p=0.04)



Notes: (s)= seconds; sEMG= surface electromyography; (V)= volts

Introduction

Concussion

Concussion Epidemiology

Concussion, a type of traumatic brain injury (TBI), is defined as a trauma induced pathophysiological process resulting from a rapid acceleration or deceleration of the brain.[1] The Center for Disease Control (CDC) estimates that 300,000 sports-related concussions occur annually in the United States (US) alone.[2] These incidences are a significant public health concern, especially in high school and collegiate athletics.[3] In the US, 1.6 to 3.8 million sports-related traumatic brain injuries occur annually while another 50-80% of incidences go unreported due to lack of injury recognition or non-discosure.[4–6] Moreover, an estimated 283,000 children aged 18 years or younger are treated in US emergency departments for sports-related TBI each year.[7] While there are many different classifications and mechanisms related to TBI, this research will focus specifically on sports-related concussion (SRC), which account for 10-15% of all sports related injuries.[8] This population is important because they are at the highest risk of sustaining multiple concussions and are at the highest risk of sustaining a subsequent musculoskeletal injury after returning to play.[9,10]

Concussion Pathophysiology

Concussion results in a neurometabolic cascade of simultaneous complex disruptions to the brain resulting in neuronal architectural damage, increased inflammation, increased neuroinflammation, elevated release of excitatory neurotransmitters, and altered cerebral blood flow.[11]These issues occur due to potassium flowing out of the damaged neuron while sodium and calcium flow in resulting in constantly triggered voltage- or ligand-gated ion channels which results in "widespread neuronal depression".[11] Furthermore, because of the ionic shifts caused by the cells attempting to restore homeostasis an "energy crisis" occurs due to the need for energy to restore the disruptions and the impacted ability to deliver energy to the brain.[12] Mitochondrial dysfunction may also occur due to the increased levels of calcium in the cell which lowers the ability of the cells to deliver ATP.[11] The mismatch in energy demands can last up to 10 days in adult animal models and relates to behavior impairments.[12,13] Clinically this process results in a series of non-specific signs and symptoms as well as changes in mental function.[14] Due to this complex pathophysiological process and the various symptoms it may cause, concussion diagnosis and management can be challenging.

Concussion Assessment

Background on Concussion Assessment

While the various signs and symptoms of concussions are well understood, concussion assessment and management remain difficult due to varying clinical presentation and subjective nature of the assessments. Some tests such as advanced neuroimaging, cerebral blood flow assessments, and fluid biomarker analysis can be used as an objective measure of detecting persisting impairments after recovery.[15] However, these tests are expensive and their usage in clinical practices is low. The current Sports Concussion Assessment Tool-5th Edition (SCAT-5) is an easy to administer sideline protocol that can be used by physicians and health care professionals to evaluate concussion following injury.[16] The SCAT-5 protocol includes an acute symptom evaluation, as well as a visual, motor, and cognitive evaluation.[16] While these standardized tests provide clinicians with symptomology and some objective measurements, they are still limited by the subjective nature of the assessments. In the athletic population, finding objective measures of injury are especially important for individuals who may not report symptoms in order to return to play.[6]

Visual, Vestibular, and Cognitive Assessments

Part of the multi-faceted approach used to evaluate concussion is a visual and cognitive evaluation. The Vestibular Ocular Motor Screening (VOMS) is a brief tool that can screen for vestibular and ocular motor impairments that occur in 60-81% of athletes following concussion.[17] The VOMS consists of seven different tests utilizing various eye movements such as smooth pursuits, saccades, and a near point convergence (NPC) test. Literature suggests that VOMS possesses high internal consistency and validity at detecting concussion and can be used as an additional tool to guide concussion management and rehabilitation.[18] The Immediate Post-Concussion Assessment and Cognitive Testing (ImPact) is a common cognitive assessment used following concussion.[19] The testing battery includes visual and verbal memory, reaction time, and processing speed to detect concussion in patients ages 12-80 years old.[20] While both of these assessments help clinicians make informed decisions about concussion diagnosis and management, they do not detect motor/postural control abnormalities following concussion. These metrics are extremely important for detecting lingering abnormalities and impacted functional movement.

Tandem Gait

Tandem gait is a commonly used assessment to identify postural control and balance deficits following concussion.[21,22] Tandem gait uses a series of single- and dual task trials to examine dynamic balance control.[21] Single task trials use a heel-to-toe walking pattern to challenge the sensorimotor system. Dual-task trials use a combination of the heel-to-toe walking pattern as well as a cognitive task to examine dynamic balance at speed. The ability of the participant to maintain an upright posture while competing a challenging gait and cognitive task at speed can be used to detect gait abnormalities that may be present following concussion. Tandem gait can also be used to detect changes in postural control following concussion.[23]

Postural Control

Relationship between Concussion and Postural Control

Postural control deficits are a noted sign of concussion, and while clinical symptomology is typically resolved in 7-14 days after injury, dynamic postural deficits have been noted up to a year following concussion.[24–29] These deficits are thought to occur due to impaired interactions between the somatosensory, visual, and vestibular systems.[30–32] While it is currently not completely understood exactly how concussion effects postural control, current literature suggests that within the first year of recovery from concussion, athletes are 1.9 to 3.5 times more likely to sustain a subsequent lower extremity musculoskeletal injury.[33] This increased injury risk is believed to be occurring due to lingering postural control deficits following concussion.[34]

Using Tandem Gait to Evaluate Postural Control Following Concussion

Following concussion, tandem gait can be used to evaluate gait and balance deficits caused by impairments in postural control.[35] Previous literature has observed a longer completion time, slower anterior and posterior velocity, greater mediolateral postural instability, and increased sway following concussion.[23] These characteristics when applied to an athlete could be to blame for the increased lower extremity injury risk following concussion. Therefore, using tandem gait as a tool to define the differences in lower extremity muscle recruitment could help guide rehabilitation from concussion as well as lead to development of objective clinical diagnostic assessments.

Surface Electromyography

Background on Surface Electromyography

Electromyogram (EMG) is the measurement of an electrical signal from the muscle produced during muscle contraction and represents the anatomical and physiological properties of muscles. Recently, EMG has become highly prevalent in clinical settings to evaluate the effectiveness of neurophysiological or musculoskeletal rehabilitation techniques.[36] However, data collection and signal processing can be difficult due to contamination that may also present itself within the signal such as external noise sources from surrounding muscles (also known as “cross talk”), movement artifacts, and the inherent noise of the electrode.[36] While this contamination may impair the presentation of the original signal, with the correct filter and rectification, surface electromyography (sEMG) can be used to observe muscle activation abnormalities.

Using Surface Electromyography to Evaluate Postural Control

Previous literature has examined the relationship between postural control and muscle activation using expensive virtual environments and transcranial magnetic stimulation.[37–39] Sensorimotor perturbations are effective at detecting lingering postural control deficits following concussion.[38] In studies that used virtual environments that delivered sensory perturbations, moving platforms that delivered motor perturbations, and sEMG sensors, they found that sensorimotor perturbation was effective at detecting lingering balance problems following mTBI.[38,39] In literature that used transcranial magnetic stimulation to observe whether asymptomatic athletes with a previous SRC would display motor cortex dysfunction, found that SRC results in subclinical motor system dysfunction due to intracortical inhibitory system abnormalities.[37] Therefore, using sEMG along with the motor and cognitive perturbations in the tandem gait protocol should be effective at detecting muscle recruitment abnormalities that may be present following concussion.

Research Purpose

The purpose of this study is to examine the relationship between lower extremity muscle recruitment in individuals with acute concussion compared to healthy control participants using instrumented tandem gait and surface electromyography.

Hypothesis

Based upon previous literature that observed greater muscle recruitment following concussion and during sensorimotor and cognitive perturbations during gait,[38,39] it is hypothesized that individuals will exhibit greater lower extremity muscle recruitment following concussion with the highest muscle activation occurring during dual-task trials.

Methods

Participants

Initially data was collected and analyzed for 11 healthy NCAA Division I athletes, 4 healthy University of Nevada Reno Students, 11 Division I athletes with concussion, of which 6 returned for a follow up symptom free. However, some participants were removed due to incomplete data sets due to equipment failure. Final analysis consisted of 11 healthy NCAA Division I athletes and one University of Nevada Reno student (8 males, 3 females; Age: 19.5±1.31 years old; Height: 178.86±8.8 cm; Weight: 88.36±23.1 kg) 9 NCAA Division I athletes with concussion (5 males, 4 females; Age: 20.22±1.79 years old ; Height: 178.65±14.5 cm; Weight: 85.81±23.2 kgs; Average days following concussion: 1.11±0.33) of which 5 came back for a follow up symptom free appointment (3 males, 2 females; Age: 19.6±0.89 years old; Height: 182.37±15.7 cm; Weight: 86.02 kgs±22.1; Average days following concussion: 30.8±29.7). Participants were excluded from the study if they self-reported any vestibular, visual, metabolic, previously existing neurological disorders, or underlying lower extremity conditions/injury that may affect the athlete's ability to stand or walk.[23] All participants signed informed consent approved by the University of Nevada Reno Institutional Review Board prior to participating.

Testing Protocol

Prior to testing participant's height, sex, weight, number of days post injury, and VOMS Change score was recorded. Avanti sEMG electrodes (2000 Hz, Delsys, Natick, MA) with a center-to-center distance of 1 centimeter and a gain of 1000Hz were applied to the muscle belly of the Tibialis Anterior, Medial Gastrocnemius, and Peroneus Longus muscles following skin preparation.[40]

Figure 2. Delsys sEMG Electrodes (2000 Hz, Delsys, Natick, MA) on the Tibialis Anterior, Peroneal, and Medial Gastrocnemius

Skin preparation consisted of 20 seconds of vigorous rubbing with an alcohol swab on the sensor site for all three sensors. After sensor placement, participants performed three trials of pseudorandomized walking protocols on a Tekscan Strideway (30 Hz, Tekscan Inc., South Boston, MA).[35]

Figure 3. Teckscan Strideway (30 Hz, Tekscan Inc., South Boston, MA) that will be used to record all trials.

The 9 total trials are three trials of protocol one (GAIT), three trials of protocol two (ST), and three trials of protocol three (DT). GAIT consisted of the participant walking normally at a self-selected pace for 5-meters to allow the participant to reach terminal velocity before reaching the stride way, turning, and walking 3-meters off the stride way. ST consisted of the participant walking heel-to-toe in a straight line for three meters down and back as fast as they can. DT consisted of the participant walking heel-to-toe down the same three-meter line while also performing a cognitive task such as serial sevens (SS). SS requires the athlete to continuously subtract by seven from a provided number. No instructions will be given by the administrator to prioritize the gait or cognitive task. During the trial, the test administer tapped their finger on a separate sEMG electrode (2000 Hz, Delsys, Natick, MA) which will be recording accelerometer data simultaneously with the trials. This will allow the trials to be accurately broken up into three phases: Pass one (P1), Turn, and Pass two (P2).[23]

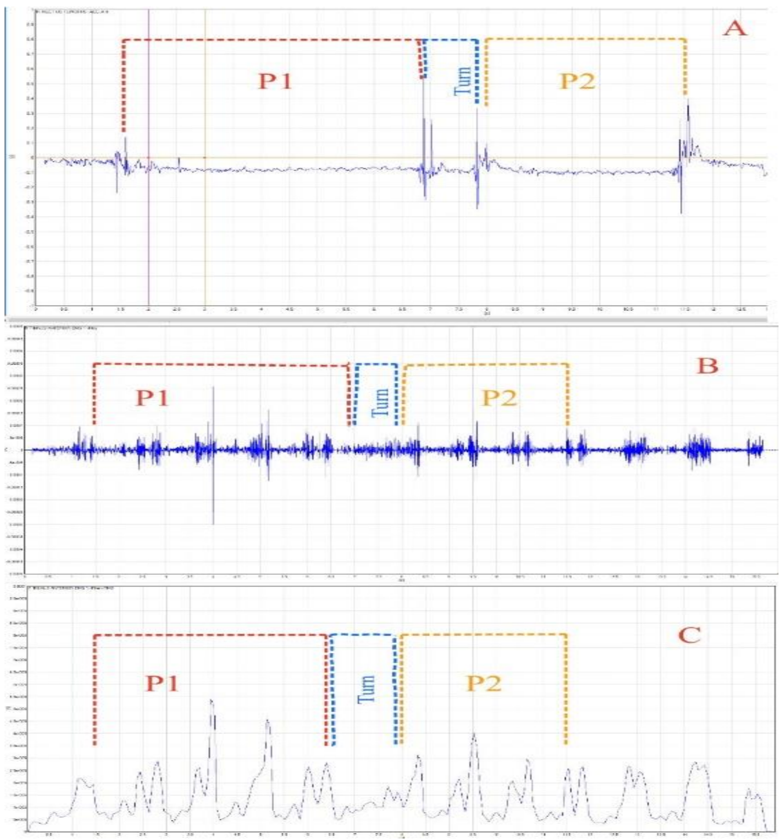


Figure 4. Accelerometer data (A) will be used to break up the surface electromyography signal (B) which will then be rectified (C).

Data Analysis

EMG data analysis was done in EMGworks Analysis (Delsys, Natick, MA). The signal was broken down into “mean activation”, P1, Turn, and P2 using the synchronized accelerometer data and band pass filtered (20Hz to 250Hz) followed by root mean square using a moving window length of 0.125s and overlap of 0.06s.[38] P1 is classified as the initial 3-meter heel-to-toe walk down the stride way, while P2 is classified as the 3-meter heel-to-toe walk back. Turn was classified as the transition period between P1 and P2.

The mean of the rectified EMG signal was normalized to each participants mean activation observed during gait using the following equation:

Equation 1.

(ST/DT Mean Activation/GAIT Mean Activation) *100

This equation will provide a normalized way to measure how much muscle activity is used during tandem gait compared to gait in each participant.

Statistical Analysis

All dependent variables were examined for skewness revealing skewness in some healthy vs concussion variables (IBM, SPSS). Therefore, a series of kruksal-wallis tests were used to analyze non-parametric variables and a series of one-way ANOVAs were uses for parametric variables in the healthy vs concussion data sets. A repeated measures ANOVA was used to assess statistical differences in concussion vs symptom free variables (IBM SPSS). Statistical significance for all variables were set at $p<0.05$. Spearman’s correlation coefficient was used to examine correlation between % muscle recruitment and VOMS change score. While Pearson’s r correlation was used to explore correlations between muscle recruitment and TG time to complete. The strength of the correlations was set as 0.2–0.39=weak, 0.4–0.59=moderate, 0.6-0.79=moderately high, ≥0.8=high>. Statistical significance was set at a $p<0.05$.

Results

There is significantly greater muscle recruitment in the TA during the turn phase in both ST and DT conditions in the healthy vs symptom free sample (CONvSF ST Turn: $F_{(1,4)}=12.22$; p=0.03; CONvSF DT Turn: $F_{(1,4)}=8.61$; p=0.04). While the rest of the data did not yield significant results, following analysis consistent trends were revealed. In general, there is a decrease in muscle recruitment of the TA and M. GAST muscles along with an increase in PER recruitment following concussion (Table 2.).

Healthy vs. Concussion

Following SRC, there is a decrease in TA and M.GAST recruitment with an increase in PER recruitment during ST trials. (Table 2&Figure 1.). DT trials have the same recruitment patterns on a lower magnitude compared to ST trials. Based on Cohen's d and p-values, there is a large difference in TA recruitment between healthy individuals and individuals with SRC during ST and DT trials of TG (Table 2&3.).

Upon evaluation of the phases of TG, there is a large increase in PER recruitment during the TURN and P2 phase (Table 4.) while the TA and M.GAST are consistently depressed following SRC. Furthermore, DT trials once again exhibit lower recruitment with the same pattern compared to ST trials. One notable difference is that during P1, ST PER recruitment has no notable difference to healthy controls however, following the TURN, muscle recruitment is increased and stays increased throughout P2. Whereas, during DT trials, P1 PER is consistently higher throughout the trial (Table 4.). Based on Cohen's d and p-values, there is a moderate to large difference between TA and PER recruitment during the phases of TG (Table 4&5.).

Concussion vs. Symptom Free

Upon symptom elevation, there is a notable overall increase in TA and M.GAST recruitment and a decrease in PER recruitment during ST and DT TG trials. (Table 6&Figure 2.) Based on Cohen's d and p-values, there is a moderate to large difference in TA and PER recruitment overall during TG. (Table 6&7.). The individual phases of TG follow the same pattern with one notable difference being in the ST PER TURN which exhibits higher muscle recruitment consistent with observations made following concussion (Table 8.) Furthermore, based on Cohen's d and p-values during the phases, there are moderate to large differences in PER recruitment during P1, TA and M.GAST recruitment during TURN, and TA and PER recruitment during P2.

Time to Complete and VOMS Change Score

There is a significant correlation between muscle recruitment and single task time to complete in symptom free individuals (p=0.01). There is also an overall negative correlation between muscle recruitment and tandem gait time to completion in all trial except for DT condition of healthy individuals peroneals and the DT condition of in the tibialis anterior of symptom free individuals (Table 10). Furthermore, there is a positive correlation between vestibular ocular motor screening change score and muscle recruitment in all conditions except for in the TA in the concussion group, and the healthy and concussion group of the M. GAST (Table 10.).

Discussion

The purpose of this study is to examine muscle recruitment abnormalities between healthy, concussed, and symptom free individuals using tandem gait and sEMG. We hypothesized that following concussion we would see an increase in muscle recruitment due to increased postural instability. This hypothesis is partially correct, we did observe increases in the muscles that provide mediolateral stability (PER). However, we observed decreases in the primary movers (TA and M.GAST) that is consistent with literature reporting decreased TG velocity following concussion.[21]

While it was hypothesized that the DT trials would exhibit the highest muscle recruitment following concussion, the results of this study demonstrate the opposite trend. During DT trials, there is consistently less muscle recruitment in all three muscles in Healthy, CON, and SF groups. This suggests that the addition of a cognitive task will cause the participant to go into a more conservative tandem stance and decrease gait velocity. This aligns with current literature done by Howell et. al. 2015 which observed an increase in COM displacement as well as a decrease in gait velocity in DT trials following concussion.[27]

Healthy vs. Concussion

Following SRC there is an overall decrease in TG velocity classified at the muscular level as a decrease in TA and M.GAST recruitment. Furthermore, there is an increase in mediolateral instability defined as an increase in PER recruitment (Table 2.). Analysis of the phases of TG revealed that the TURN phase is the mechanism behind the mediolateral instability occurring during the trial, particularly during ST trials (Table 4.). This aligns with current literature which supports the notion that complex tasks requiring greater cortical input such as turning and subsequent gait initiation will exhibit greater impairment following concussion.[30] The turning task of tandem gait also stresses vestibular, visual, and somatosensory systems, all of which effect postural control and are expected to be impaired following SRC.

Concussion vs. Symptom Free

In the concussion vs symptom free sample, there is a clear recovery of medio-lateral instability with all three phases of tandem gait demonstrating an increase in primary mover recruitment, as well as a decrease in stabilizer recruitment (Table 6&8). However, the discrepancy between the symptom free and healthy data represents the lingering postural control deficits expected following concussion. At symptom free, athletes still have about a 10% and 25% difference in their TA, 8%-7% difference in PER, and 5%-15% difference in M.GAST when compared to their healthy counterparts. Furthermore, in ST TURN PER, there is observable mediolateral instability still present (Table 8.). However, recovery of stability in the SF group is improved compared to their concussed evaluation as evident by the stability present in ST P2 PER (Table 8.)

Time to Complete and VOMS Change Score

There is an overall moderate to strong negative correlation between time to complete between time to complete tandem gait and % Gait. Demonstrating that muscle recruitment tends to trend in the opposite direction of time. For example, as time to complete tandem gait increases, muscle recruitment decreases and vice versa (Table 6). This confirms that the self-paced nature of tandem gait relates to the abnormal muscle recruitment patterns observed following concussion. This is expected as less velocity will mean less overall motor unit recruitment. There is also a weak to moderate correlation between VOMS change score and muscle recruitment, which aligns with current center of pressure literature.[23]

Implications

While athletes recover mediolateral stability and return to higher sagittal plane velocity, they are on average still less stable than their healthy counterparts. This is extremely important, while athletes are no longer experiencing the clinical symptomology of concussion, they are beginning return to play with medio-lateral instability still present. This instability could be correlated with the 1.6-3.5x increase in lower extremity MSK injury risk that athletes experience for up to a year following concussion. Implementing neuromuscular rehabilitation concurrent or prior to phase one of the return to play process could increase proprioceptive awareness, and decrease this injury risk before athletes return to the field.

Future Considerations

In the future, researchers should continue to analyze the trends consistent with this research and center of pressure research done by Murray et al.[23] Finding the link between increases in excursion, sway, and sEMG following concussion would further explain the trends present in this data.[23] Furthermore, muscle timing patterns should be analyzed next to observe how delayed cortical silent periods may be affecting the coordination of muscle recruitment.[37]

Limitations

This study is not without limitations. The small sample size and low power of the study may be affecting the trends present in the data. Furthermore, sensor placement and movement during trials could cause signal artifacts that could lead to overestimation of muscle recruitment. However, the filter design was consistent with other sEMG research which also used a dynamic task and similar muscle groups which should eliminate these artifacts from all trials.[38] The walking mechanics and turning patterns of the participants were not tightly controlled. In our healthy sample 66.6% of participants performed an on-point (both feet on ground) while 33.3% of individuals performed an off-point (one-foot leaves ground) turn. Whereas in our concussion and symptom free data sets 100% of participants performed an on-point turn. This difference in turn types could account for the PER recruitment observed during the TURN.

Conclusion

Using tandem gait with sEMG was effective at observing muscle recruitment abnormalities that occur post SRC. Increased mediolateral instability and decreased gait velocity classified as an increase in peroneal recruitment and decreased anterior tibialis and medial gastrocnemius recruitment was observed following concussion. Upon symptom free evaluation, recovery of medio-lateral stability denoted by decreased personal recruitment, and increased anterior tibialis and medial gastrocnemius recruitment was observed. However, athletes at symptom free are still exhibiting slightly higher levels of medio-lateral instability when compared to healthy controls representing the need for stability specific rehabilitation protocols before or during the initial stage of return to play.

References

1. Stillman A, Alexander M, Mannix R, Madigan N, Pascual-Leone A, Meehan WP. Concussion: Evaluation and management. *Cleve Clin J Med*. 2017;84(8):623-630. doi:10.3949/ccjm.84a.16013

2. Thurman DJ, Branche CM, Sniezek JE. The epidemiology of sports-related traumatic brain injuries in the United States: recent developments. *J Head Trauma Rehabil*. 1998;13(2):1-8. doi:10.1097/00001199-199804000-00003

3. Sarmiento K. Emergency Department Visits for Sports- and Recreation-Related Traumatic Brain Injuries Among Children — United States, 2010–2016. *MMWR Morb Mortal Wkly Rep*. 2019;68. doi:10.15585/mmwr.mm6810a2

4. Langlois JA, Rutland-Brown W, Wald MM. The Epidemiology and Impact of Traumatic Brain Injury: A Brief Overview. *J Head Trauma Rehabil*. 2006;21(5):375-378.

5. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported Concussion in High School Football Players: Implications for Prevention. *Clin J Sport Med*. 2004;14(1):13-17.

6. Llewellyn T, Burdette GT, Joyner AB, Buckley TA. Concussion Reporting Rates at the Conclusion of an Intercollegiate Athletic Career. *Clin J Sport Med*. 2014;24(1):76-79. doi:10.1097/01.jsm.0000432853.77520.3d

7. Epidemiology of Sport-Related Concussion - ClinicalKey. Accessed June 16, 2022. https://www.clinicalkey.com/#!/content/playContent/1-s2.0-S0278591920350791?returnurl=https:%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0278591920350791%3Fshowall%3Dtrue&referrer=https:%2F%2Fpubmed.ncbi.nlm.nih.gov%2F

8. Eapen B, Cifu DX. *Rehabilitation After Traumatic Brain Injury*. Elsevier Health Sciences; 2018.

9. Howell DR, Lynall RC, Buckley TA, Herman DC. Neuromuscular Control Deficits and the Risk of Subsequent Injury after a Concussion: A Scoping Review. *Sports Med Auckl NZ*. 2018;48(5):1097-1115. doi:10.1007/s40279-018-0871-y

10. McPherson AL, Nagai T, Webster KE, Hewett TE. Musculoskeletal Injury Risk After Sport-Related Concussion: A Systematic Review and Meta-analysis. *Am J Sports Med*. 2019;47(7):1754-1762. doi:10.1177/0363546518785901

11. Howell DR, Southard J. THE MOLECULAR PATHOPHYSIOLOGY OF CONCUSSION. *Clin Sports Med*. 2021;40(1):39-51. doi:10.1016/j.csm.2020.08.001

12. Dynamic changes in local cerebral glucose utilization following cerebral concussion in rats: evidence of a hyper- and subsequent hypometabolic state -

ScienceDirect. Accessed August 25, 2022. https://www.sciencedirect.com/science/article/abs/pii/000689939190755K?via%3Dihub

13. Giza CC, Hovda DA. The New Neurometabolic Cascade of Concussion. *Neurosurgery*. 2014;75(0 4):S24-S33. doi:10.1227/NEU.0000000000000505

14. McCrory P, Meeuwisse W, Dvorak J, et al. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*. 2017;51(11):838-847. doi:10.1136/bjsports-2017-097699

15. Kamins J, Bigler E, Covassin T, et al. What is the physiological time to recovery after concussion? A systematic review. *Br J Sports Med*. 2017;51(12):935-940. doi:10.1136/bjsports-2016-097464

16. Sport concussion assessment tool - 5th edition. *Br J Sports Med*. Published online April 26, 2017:bjsports-2017-097506SCAT5. doi:10.1136/bjsports-2017-097506SCAT5

17. Using change scores on the vestibular ocular motor screening (VOMS) tool to identify concussion in adolescents. Accessed August 25, 2022. https://www.tandfonline.com/doi/epub/10.1080/21622965.2021.1911806?needAccess=true

18. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) Assessment to Evaluate Concussions. *Am J Sports Med*. 2014;42(10):2479-2486. doi:10.1177/0363546514543775

19. Merritt VC, Bradson ML, Meyer JE, Arnett PA. Evaluating the test-retest reliability of symptom indices associated with the ImPACT post-concussion symptom scale (PCSS). *J Clin Exp Neuropsychol*. 2018;40(4):377-388. doi:10.1080/13803395.2017.1353590

20. What is ImPACT Testing? | ImPACT Applications. Published May 21, 2019. Accessed August 25, 2022. https://impactconcussion.com/new-to-impact/

21. Howell DR, Osternig LR, Chou LS. Single-task and dual-task tandem gait test performance after concussion. *J Sci Med Sport*. 2017;20(7):622-626. doi:10.1016/j.jsams.2016.11.020

22. Davis GA, Iverson GL, Guskiewicz KM, Ptito A, Johnston KM. Contributions of neuroimaging, balance testing, electrophysiology and blood markers to the assessment of sport-related concussion. *Br J Sports Med*. 2009;43(Suppl 1):i36-i45. doi:10.1136/bjsm.2009.058123

23. Murray NG, Moran R, Islas A, et al. Sport-related concussion adopt a more conservative approach to straight path walking and turning during tandem gait. *J Clin Transl Res*. 2021;7(4):443-449.

24. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute Effects and Recovery Time Following Concussion in Collegiate Football PlayersThe NCAA Concussion Study. *JAMA*. 2003;290(19):2556-2563. doi:10.1001/jama.290.19.2556

25. Dual-Task Effect on Gait Balance Control in Adolescents With Concussion - ClinicalKey. Accessed July 21, 2022. https://www.clinicalkey.com/#!/content/playContent/1-s2.0-S0003999313003213?returnurl=https:%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0003999313003213%3Fshowall%3Dtrue&referrer=https:%2F%2Fpubmed.ncbi.nlm.nih.gov%2F

26. Howell DR, Osternig LR, Chou LS. Adolescents Demonstrate Greater Gait Balance Control Deficits After Concussion Than Young Adults. *Am J Sports Med*. 2015;43(3):625-632. doi:10.1177/0363546514560994

27. Howell DR, Osternig LR, Chou LS. Return to Activity after Concussion Affects Dual-Task Gait Balance Control Recovery. *Med Sci Sports Exerc*. 2015;47(4):673-680. doi:10.1249/MSS.0000000000000462

28. Murray NG, Szekely B, Moran R, et al. Concussion history associated with increased postural control deficits after subsequent injury. *Physiol Meas*. 2019;40(2):024001. doi:10.1088/1361-6579/aafcd8

29. Schmidt JD, Terry DP, Ko J, Newell KM, Miller LS. Balance Regularity Among Former High School Football Players With or Without a History of Concussion. *J Athl Train*. 2018;53(2):109-114. doi:10.4085/1062-6050-326-16

30. Murray NG, Reed-Jones RJ, Szekely BJ, Powell DW. Clinical Assessments of Balance in Adults with Concussion: An Update. *Semin Speech Lang*. 2019;40(1):48-56. doi:10.1055/s-0038-1676451

31. Guskiewicz KM, Perrin DH, Gansneder BM. Effect of Mild Head Injury on Postural Stability in Athletes. *J Athl Train*. 1996;31(4):300-306.

32. Balance Assessment in the Management of Sport-Related Concussion - ClinicalKey. Accessed July 25, 2022. https://www.clinicalkey.com/#!/content/playContent/1-s2.0-S0278591910000785?returnurl=https:%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS0278591910000785%3Fshowall%3Dtrue&referrer=https:%2F%2Fpubmed.ncbi.nlm.nih.gov%2F

33. Acute Lower Extremity Injury Rates Increase after Concussion... : Medicine & Science in Sports & Exercise. Accessed August 25, 2022. https://journals.lww.com/acsm-msse/Fulltext/2015/12000/Acute_Lower_Extremity_Injury_Rates_Increase_after.1.aspx

34. Murray N, Belson E, Szekely B, et al. Baseline Postural Control and Lower Extremity Injury Incidence Among Those With a History of Concussion. *J Athl Train*. 2020;55(2):109-115. doi:10.4085/1062-6050-187-19

35. Howell DR, Oldham JR, DiFabio M, et al. Single-Task and Dual-Task Gait Among Collegiate Athletes of Different Sport Classifications: Implications for Concussion Management. *J Appl Biomech*. 2017;33(1):24-31. doi:10.1123/jab.2015-0323

36. Chowdhury RH, Reaz MBI, Ali MABM, Bakar AAA, Chellappan K, Chang TaeG. Surface Electromyography Signal Processing and Classification Techniques. *Sensors*. 2013;13(9):12431-12466. doi:10.3390/s130912431

37. LONG-TERM AND CUMULATIVE EFFECTS OF SPORTS CONCUSSION ON MOT... : Neurosurgery. Accessed July 30, 2022. https://journals.lww.com/neurosurgery/Fulltext/2007/08000/LONG_TERM_AND_CUMULATIVE_EFFECTS_OF_SPORTS.13.aspx

38. Rao HM, Talkar T, Ciccarelli G, et al. Sensorimotor conflict tests in an immersive virtual environment reveal subclinical impairments in mild traumatic brain injury. *Sci Rep*. 2020;10:14773. doi:10.1038/s41598-020-71611-9

39. Jacob D, Unnsteinsdóttir Kristensen IS, Aubonnet R, et al. Towards defining biomarkers to evaluate concussions using virtual reality and a moving platform (BioVRSea). *Sci Rep*. 2022;12:8996. doi:10.1038/s41598-022-12822-0

40. Leg muscle activity during tandem stance and the control of body balance in the frontal plane - ScienceDirect. Accessed July 11, 2022. https://www.sciencedirect.com/science/article/pii/S1388245712007730?via%3Dihub