

Real-Time Concurrent Neurophysiological Responses to Dynamic In-Motion Physical and Cognitive Functional Tasks in Division I Athletes

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Background: Quantitative electroencephalography (qEEG) offers sports medicine clinicians insight into the neurophysiological connection between the brain and musculoskeletal system. Dysregulation in the brain's neural state has been linked with altered biomechanical and/or musculoskeletal performance associated injury; however, comparative benchmark data among uninjured athletes without brain and/or musculoskeletal injury remain limited.

Hypothesis: Evaluating real-time qEEG neurophysiological and physiometric neurological brain responses while performing physical and cognitive functional tasks will offer clinicians performance insight to the neuromuscular preparedness in healthy Division I athletes.

Study Design: Descriptive prospective case series.

Level of Evidence: Level IV.

Methods: A total of 24 healthy female (n=11) and male (n=13) National Collegiate Athletic Association (NCAA) Division I athletes from multiple sports volunteered to participate in a qEEG neurophysiological and functional task assessment. A 21-channel Dry headset collected neurophysiological brain wave activity representing participants' level of attention, workload and sensorimotor rhythm (SMR) pre- and post-physical and cognitive tasks. Physiometric dependent variables included heartrate, respiration rate, heartrate variability, galvanic skin response, trapezius electromyography and peripheral temperature. Participants had no diagnosed attention deficits, learning impairments, and/or orthopaedic injuries.

Results: Healthy Division I athletes had balanced/regulated neurophysiological levels of change in neurophysiological activity. Brain connectivity, attention, and workload metrics were significantly higher in men ($P \leq 0.05$). There were no sex or hemisphere differences at baseline for SMR; however, there were significant SMR differences pre- to post- for motor imagery tasks ($P \leq 0.05$). There were relatively strong positive correlations between brain activity and physiometric performance (0.81-0.85), as well as, brain symmetry, workload, and attention (0.65-0.85).

Conclusion: Real-time qEEG brain mapping of neurophysiological and physiometric responses during functional and cognitive tasks provide standard performance benchmarks for healthy, Division I athletes.

Clinical Relevance: Monitoring qEEG neurophysiological and physiometric benchmarks of healthy athletes can offer clinicians performance insight into neuromuscular preparedness.

Keywords: brain mapping; mirror neuron network; neuromuscular control; neurophysiological; neuroplasticity; physiometrics; quantitative electroencephalography (qEEG)

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Musculoskeletal function depends greatly on the excitability and efficiency of peripheral nervous system (PNS) and central nervous system (CNS) processes.^{2,22,29,32,36} Alteration, via distractions, fatigue and/or injury, modify the CNS processes that appear to effect afferent input from joint mechanoreceptors, muscle spindles, and other receptors in the skin, thus altering or limiting musculoskeletal function.^{22,32,38,39} Neurological disruptions alter CNS processing of afferent input, although no changes in the actual afferent signals may exist. As a result, clinicians often implement such alteration as key components to stimulate both training and rehabilitation interventions designed to establish and/or retrain neurologic properties necessary to safely compete in sports and functional activities. Recent studies have focused on identifying isolated altered brain state/CNS function associated with anterior cruciate ligament injury by way of quantitative electroencephalography (qEEG) and functional magnetic resonance imaging (fMRI).^{15,22,29,33,41} Specifically, these findings have indicated alterations to cognitive (focus, attention) and/or physical (musculoskeletal activation/reaction time) function are associated with CNS-neurological alterations or impairment.³³⁻³⁵ However, these studies were limited in identifying the relationship between the altered brain state and physiological influences associated with injury. Similar to many clinical assessments used to simultaneously assess changes in neurological and physical function these studies served as a foundation for further objective investigations specific to better understand the effect the brain's function has on the functional capacity of the musculoskeletal system.^{29,32} As a result, there is a need to further investigate the role of the brain and assessment techniques that attain objective data exclusive to both the neurological and physiological properties among different sexes/athletic populations. Here, a primary objective would be to equip clinicians with objective and actionable data or resources to assist and direct decisions related to pre- and postinjury progressions.^{23,29,39}

Neurophysiological assessments target neuromuscular and cognitive functions of the CNS, exclusive to the functional capacity of the brain.³⁶ Normal or appropriate biomechanical and motor function for sport tasks rely extensively on the connection of brain-to-body synergistic communication.^{14,29,36} Homeostatic balance of brain activity appears to be necessary for appropriate functional behaviors that demonstrate reasonable emotional, cognitive, and motor responses associated with one's environment.⁵ However, lack of mental focus, poor attention, neurological fatigue, and injury have been associated with disturbances in the neural excitability and functioning properties between the brain's CNS and the PNS.^{5,29,41} Such conditions can result in alterations in neurological messages between afferent joint mechanoreceptors, muscle spindles, and other nervous system receptors resulting in less than optimal efferent motor responses during functional activities.^{29,36} Physiometric parameters are also influenced in an altered brain state that influences heart rate (HR), muscular tension, heart rate variability (HRV), and respiration rate

(RR).^{1,12,24,29} Recent assessment and rehabilitative techniques have placed great emphasis on targeting the properties of the brain and CNS that control motor function to prevent faulty motor responses.^{1,3,29,41} There is a need to investigate how the brain manages and collectively influences afferent and efferent CNS input and the effect such changes have on physiometric parameters and/or the musculoskeletal system as it relates to injury, performance, and/or return to play. As a result, clinicians and researchers continue to evaluate emerging technologies targeting brain and physiological function as it relates to motor performance and/or injury.

fMRI has been reported to be a reliable source in detecting increased/decreased metabolic brain activity associated with musculoskeletal function.^{1,9,14} Here, clinicians can identify fluctuations in brain region activity based on proliferation and/or diffusion of blood oxygen migrating to and from different regions of the brain, respectively. The areas of the brain that emulate increased blood-oxygen-level-dependent signals, commonly referred to as the "BOLD" signals, is assumed to represent an increased brain electrical activity to the specific identified area of blood proliferation. Blood flow is the primary fMRI signal representing brain energy metabolism that is thought to identify the workload regions of the brain during cognitive and somatic activities.^{14,15,32} These fMRI results are inferred based on several studies performing motor activities in the restricted confines of the fMRI system.¹⁴ While dynamic activities are difficult to simulate within the fMRI device, high-risk landing knee valgus frontal plane moments have been reported to correlate with increased fMRI signal in brain centers responsible for visual processing, spatial navigation, and movement foreshadowing associated with rewarding behaviors.¹⁴ These findings suggest the visual and proprioceptive processing areas responsible for neuromuscular control adaptations require increased brain energy metabolism as seen with increases in oxygenated blood flow to those brain regions. However, there is a lack of evidence linking fMRI blood oxygenation and brain electrical activity to real-time dynamic and/or physical tasks.³² Further, the static fMRI images provide a momentary snapshot of brain activity and not a cumulative summary regarding functional activity. As a result, fMRI is not truly indicative of the dynamic neurological alterations associated with true musculoskeletal functional tasks.¹² Although provocative and insightful, the fMRI data is an indirect measure of neurophysiological activity.^{8,12,15} To better understand the neuromuscular-brain interface, there is a need for assessment techniques and technologies that monitor brain electrical function associated with somatic functional tasks directly, in real-time, and continuously.

Recent neurophysiological measures, such as qEEG, objectively assess and quantify the neuromuscular and cognitive functions of the CNS, exclusive to the brain and body's ability to communicate, collaborate, and adapt to the environment.^{1,10,37} Such neural brain activity corresponds with true, real-time cause and effect change to neurophysiological properties and function.²⁹ Observed functional behaviors associated with brain

Table 1. Brain wave frequencies and expected behavior via qEEG signals

Brain wave	Wave frequency, Hz	Behavior
Delta	0.1-4.0	Sleep
Theta	4-8	Presleep, sluggish
Alpha	8-12	Relaxed comfortable, degree of focus
Mu	7.5-12.5	Sensorimotor control opposite extremity
SMR	12-15	Attention/energy to train and learn motor skills
Beta	12-31	Conscious focus and thought for logical thinking
Gamma	32-100	Higher brain function related to working memory and problem solving

qEEG, quantitative electroencephalography; SMR, sensorimotor rhythm.

wave activity, commonly referred to as a brain map, can be used to differentiate whether the brain is regulated (functioning effectively) or dysregulated (functioning ineffectively).³⁷ Regulation and dysregulation of brain wave activity is determined by the electrical signals emitted from the brain that are associated with appropriate/inappropriate behaviors respectively.

The electrophysiological activity or brain waves can be documented and plotted to form a mapped representation of the collective functioning frequencies within specific regions of the brain associated with particular cognitive or motor behaviors. As highlighted in Table 1, brain wave frequency behaviors are specified to occur in specific neurological ranges of brain wave activity associated with expected or appropriate behavior. Known as the mirror neuron network (MNN), brain mapped images provide quantitative and anatomic measures that can be used to determine function and irregularities if present.^{5,11} In short, higher brain wave frequencies (in Hertz) indicate higher levels of cognitive and/or physical efforts associated with functional tasks. As such, MNN can be used to establish normalized benchmarks of brain wave frequencies among populations during cognitive and/or physical tasks. Monitoring change in MNN data has been used to assist in identifying and correcting behavioral patterns associated with attention deficits and/or sleeping disparities.^{4,5,11,28,29,41} Aligning the appropriate brain state/frequency is critical when establishing an appropriate behavioral response.

Brain hemispheric asymmetry, brain workload, brain attention processing, and brain connectivity have been among the primary key performance variables measured with qEEG used to determine brain neural function and regulation.⁵ In healthy people, appropriate brain frequencies will determine whether the brain workload and attention metrics can function at a regulated or appropriate fashion.⁵ Brain workload is the brain's ability to collectively and efficiently connect and use multiple brain centers to process and attain appropriate behaviors. The

attention metric of the brain evaluates whether brain wave frequencies align appropriately with situations that require heightened focus and precision in activities, such as executing motor skills or comprehending mathematical concepts.^{4,5} Ultimately, the brain workload assists in attaining focused or comprehensive behaviors that are appropriate and adaptable to the environmental circumstances.

Recent literature suggests monitoring qEEG physiometric signals and key performance variables are advantageous in identifying real-time acute cortical changes, thus offering insight into one's readiness for a physical task.^{5,15,29} Monitoring key performance indicators of neurophysiological function in healthy uninjured athletes may be valuable in establishing expectations for normal neural performance that maybe use to refine training or exercise programs associated with sport and/or rehabilitation. It seems reasonable to establish a comprehensive neurophysiological profile of a diverse group of healthy athletes to serve as a benchmark for National Collegiate Athletic Association (NCAA) Division I athletic populations. Thus, the purpose of this prospective investigation was to evaluate task-driven, neurophysiological and physiometric responses to establish a normative database or benchmarks of neural functioning properties of the brain during functional and cognitive tasks in healthy uninjured Division I athletes.

METHODS

Study Design and Population

Setting

The study was conducted at a NCAA Division I university athletic training facility.

Participants

A total of 33 healthy uninjured NCAA Division I athletes volunteered to participate in the study information session. Athletes were excluded from the study if they had a current

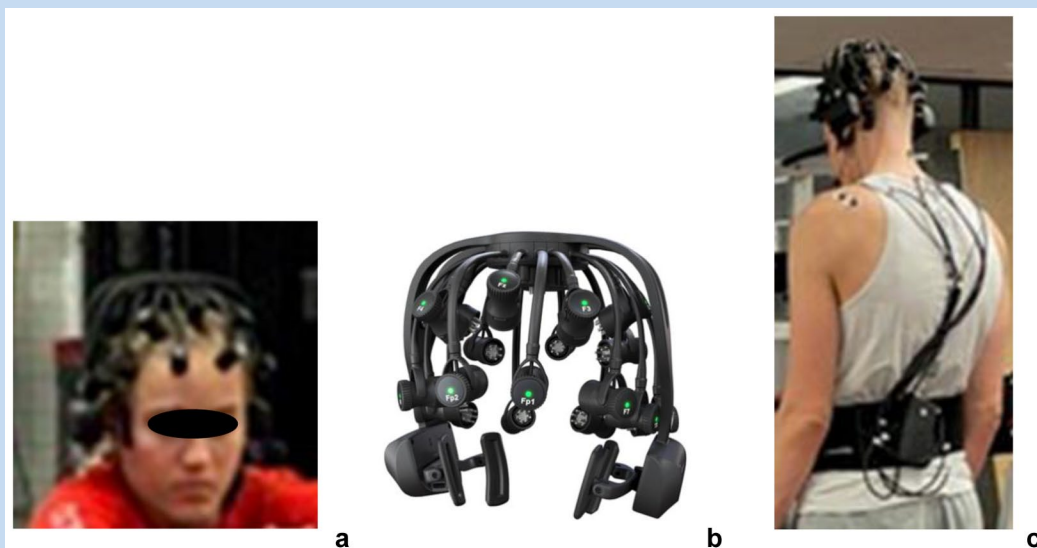


Figure 1. CGX Quick-20r Version 2, 21-channel dry EEG headset and data collection system. (a) Positioning of headset, (b) headset, (c) data collection system. EEG, electroencephalography.

injury, a current history of an attention deficit, anxiety, and/or orthopaedic injury that had disqualified the athlete from participation over the past 5 years. A total of 24 healthy uninjured Division I collegiate female ($n=11$) and male ($n=13$) athletes (age, 19.19 ± 1 years; height, 173.35 ± 7.35 cm; weight, 79.78 ± 13.26 kg), from a variety of sports (9 baseball, 2 football, 3 soccer, 1 Lacrosse, 7 swimming and diving, 1 basketball, and 1 track and field), were selected randomly and signed an institutional review board (IRB)-approved consent form. Inclusion criteria consisted of participants being >18 years of age and to have no current injuries. Nine participants were excluded due to the occurrence of an acute/chronic musculoskeletal or head injury resulting in being disqualified to participate in sport over the past 5 years. Each participant received a real-time qEEG neurophysiological cognitive and functional assessment lasting approximately 30 to 45 minutes.

Consent

This study was approved by a University IRB (SM21065). All study participants attended an information session regarding the study format and procedures before signing an informed consent. No incentives or payments were received for participating in this study.

Measures

Participants were part of a descriptive prospective case series to investigate real-time brain electrical activity, physiometrics, and neurophysiological function as it relates to movement and reaction time tasks associated with sport, such as balance, single-limb strength tasks and agility tasks.^{16,17,18,29} qEEG measures of the electrical brain-wave patterns from cortical

activity were recorded simultaneously with the functional tasks to evaluate the CNS processing efficiency, power spectra, amplitude, and connectivity of brain function.^{17,18,29}

Each assessment session began with collection of a preassessment profile and medical history, which was uploaded into the CLR Advantage system. All neurophysiological assessments mimicked those previously reported in Mangine et al²² with the CLR Neurosthenics and CLR Advantage Neurophysiological Assessment Platform.^{23,29} Reported to be valid and reliable measures, a CGX Quick-20r Version 2, 21-channel dry EEG headset was worn to collect brain activity while participants simultaneously performed the cognitive and motor tasks associated with sport and movement assessments.²⁹ The feasibility and practical application of the physical and cognitive tasks offered simulation circumstances often experienced by athletes while competing in sport (Figure 1).

The CGX AIM physiological monitoring system was used to monitor and transmit physiometrics dependent variables in HR, HRV, RR, peripheral temperature, and galvanic skin response (GSR).^{23,29} The Bluetooth configuration of the CLR Advantage headset and the CGX AIM transducer allowed for a continuous, wireless, and secure stream of biometric data to the CLR Advantage system. This allowed participants to perform various physical tasks from multiple positions in a clinical type setting with limited restriction and facilitated the simultaneous capture of neurophysiological compensation and accommodations during the physical and cognitive tasks (Figure 2).

The neurophysiological assessment consisted of baseline evaluation followed by a series of cognitive challenges and motor imagery, reaction time, and physical assessment tasks. Each assessment was designed to stimulate and measure



Figure 2. Example of functional and reaction time tasks: (a) double leg squat, (b) single leg squat, (c) reaction time to a video display, (d) force plate assessments.

particular cognitive functions of the brain.^{13,17,18,30} Before testing, baseline data was established by monitoring brain wave activity while participants sat in a rested and relaxed state with eyes opened and eyes closed.^{29,30} Once baselines were established, participants performed the cognitive assessment tasks including a Stroop test and positive imagery and anticipation/reaction time tasks. The functional movement assessment emphasized balance, gait, agility, and functional mobility of primarily the lower extremity.^{2,13,19,28,36} The physical tasks included: an

unloaded double-leg and bilateral single-leg squat and bilateral single leg step down, side step, and single-leg balance.

The MNN activity, which offers insight to the regional activity and the hemispherical balance/symmetry of the brain, was established during the Covert Imagery, Companion Overt Motor tasks, and functional movement tasks.^{17,18,23,29} EEG brain frequency bands; Delta (0.1–4Hz), Theta (4–8Hz), Alpha (8–12Hz), SMR (12–15Hz) and Beta 1–3 (12–30Hz) were monitored to attain a perspective on the participants' brain

Table 2. Group and sex demographic data for attention, workload, SMR, HR, and RR

	Attention ^a	Workload ^b	SMR ^c	HR, bpm	RR ^d
Average ($\pm$ SD) ^e	1.23 ($\pm$ 0.11)	0.81 ($\pm$ 0.07)	−0.004 ($\pm$ 0.009)	67.8 ($\pm$ 8.3)	14.99 ($\pm$ 1.8)
Female	1.39	0.79	−0.004	74	14.99
Male	1.05	0.91	−0.004	64	14.01
Sex difference ^f	0.02*	0.04*	0.07	0.03*	0.39

bpm, beats per minute; HR, heartrate; RR, respiration rate; SMR, sensorimotor rhythm.

^aA metric of brain focus from brain power spectra, physical units cancel out resulting in dimensionless indicies.

^bA brain capability ratio derived from power spectra that cancels out resulting in dimensionless indicies.

^cBrain wave representing sensorimotor cortex activity represented in microvolts.

^dAverage respiration completed per 1 minute.

^eCombined total average for male and female participants.

^fP value.

* $P \leq 0.05$.

engagement pertaining to inhibition, memory, decisiveness, efficiency, and emotions.^{14,17,37} Collectively, the assessment tasks were used to measure fluctuations in brain attention and workload levels.^{23,29} Each assessment session was concluded by generating an Intheon Neuroscale analytic report for each participant, as reported previously.²⁹ The primary dependent variables monitored were cognitive function relative to attention, workload capability, and sensorimotor rhythm (SMR) asymmetries.²⁷ Secondary biological variables, such as HR, HRV, RR, peripheral temperature, trapezoidal electromyography (EMG)/muscle activity and GSR were also monitored.

Statistical Analysis

Descriptive data for healthy, uninjured Division I collegiate athletes were established (Table 2).

Neurophysiological trends in each dependent variable were assessed using a series of independent *t* tests to evaluate differences in neurophysiological trends for left to right brain hemispheric symmetry, sex, and pre- to postmotor imagery ($P < 0.05$), (Tables 3 and 4). A Pearson's product correlation coefficient was used to assess relationships between brain state functions for connectivity, workload, attention, HR, and GSR ($P < 0.05$) (Table 5).

RESULTS

As measured by qEEG, the neurophysiological trends in healthy, uninjured Division I college athletes characteristics were consistent with normal healthy brain activity as assessed with neurocognitive and physiological functional tasks (Table 2). An independent Student *t* test revealed regulated and consistent brain state function with left-to-right brain symmetry in uninjured, healthy athletes ($t_{23} = 3.7$; $P \leq 0.05$) (Tables 3, 4 and 5). Regulatory brain state functions for connectivity, workload,

attention, and SMR had moderate-to-strong correlations between biological biomarkers (0.81-0.85; $P \leq 0.01$) (Table 5).

DISCUSSION

The primary objective of this paper was to investigate standard brain neurophysiological patterns among different sexes utilizing qEEG and physiometric data in healthy, uninjured Division I athletes. Our results demonstrated healthy, uninjured Division I athletes (Table 2) attained standard levels of change in key performance indicators such as brain attention, workload capability, cognitive function, and SMR asymmetry (Tables 3, 4, and 5).^{7,19,21,27,32} Biological variables, such as HR, HRV, RR, peripheral temperature, trapezoidal EMG and GSR, demonstrated common healthy fluctuations as well.^{5,21,22,29,32}

Assessing the brain-to-body connection using real-time inquiries has been highly dependent on monitoring neural change in key performance indicators, such as neural connectivity, brain attention, workload, and SMR.²⁹ These key performance indicators are considered to be adaptable in conjunction with challenges in reaction time, memory/focus, and visual-spatial abilities.^{14,15,21,29,40} The current study supports these findings as brain attention, workload, and SMR metrics all had a variety of moderate to strong relationships with secondary biological metrics associated with arousal and stress in conjunction with task completion, as reported in Table 5.³⁰ Healthy, uninjured Division I athletes demonstrated regulated and balanced hemispheric brain activity, thus contributing to stable neurophysiological performance outcomes across dynamic environments. Outcomes such as these could be used as actionable assessment metrics to gain insight into an athlete's readiness to participate in sport or to monitor performance along a timeline.

Table 3. Same-side hemispheric differences in SMR qEEG activity for left and right brain hemispheres for group and sex pre- to post-MI

	L pre-MI ^a	L post-MI ^b	Left pre-MI to post-MI <i>P</i> value	R pre-MI ^c	R post-MI ^d	Right pre-MI to post-MI <i>P</i> value
Total group average ^e	-0.0037 ± 0.001	-0.0002 ± 0.013	0.03*	-0.0036 ± 0.01	-0.0014 ± 0.01	0.04*
Female average	-0.0033 ± 0.001	0.0003 ± 0.012	0.03*	-0.0039 ± 0.01	-0.0010 ± 0.01	0.03*
Male average	-0.0038 ± 0.002	-0.0005 ± 0.013	0.03*	-0.0034 ± 0.01	-0.0016 ± 0.01	0.04*
Female to male <i>P</i> value	0.8	0.9		0.7	0.9	
L-R pre MI <i>P</i> value			0.97			
L-R post MI <i>P</i> value			0.39			

MI, motor imagery; qEEG, quantitative electroencephalography.

^aLeft brain hemisphere qEEG at baseline.

^bLeft brain hemisphere qEEG post-MI.

^cRight brain hemisphere qEEG at baseline.

^dRight brain hemisphere qEEG post-MI.

^eAverage scores of all female and male participants.

^fLeft to right hemisphere qEEG pre-MI for the group.

^gLeft to right hemisphere qEEG post-MI for the group.

**P* ≤ 0.05

Table 4. Comparing differences in left and right brain hemispheres for pre-MI and post-MI qEEG activity by group and sex

	L pre-MI ^a	R pre-MI ^b	Left pre-MI to right pre-MI <i>P</i> value	L post-MI ^c	R post-MI ^d	L post-MI to right post-MI <i>P</i> value
Total group average ^e	-0.0037 ± 0.001	-0.0036 ± 0.01	0.87	-0.0002 ± 0.013	-0.0014 ± 0.01	0.22
Female average	-0.0033 ± 0.001	-0.0039 ± 0.01	0.27	-0.0003 ± 0.012	-0.0010 ± 0.01	0.38
Male average	-0.0038 ± 0.002	-0.0034 ± 0.01	0.31	-0.0005 ± 0.013	-0.0016 ± 0.01	0.28
Female to male <i>P</i> value	0.36	0.45		0.39	0.42	

MI, motor imagery; qEEG, quantitative electroencephalography.

Group Average: Average scores of all female and male participants.

^aLeft brain hemisphere qEEG at baseline.

^bRight brain hemisphere qEEG at baseline.

^cLeft brain hemisphere qEEG post-MI.

^dRight brain hemisphere qEEG post-MI.

^eAverage scores of all female and male participants.

**P* ≤ 0.05

The sex differences noted in the current study revealed some potential sex bias regarding attention and workload. Sex differences are common developmental factors associated with brain maturity, age, and health status.¹⁵ Typically, female participants demonstrate higher levels of developmental brain

maturity compared with male participants at a rate of approximately 1 to 3 years earlier in age at preadolescence to adolescence development.⁵ As such, brain workload and attention metrics among sex are likely to be different regarding motor function.^{18,22,24,29} Previous literature reported age-related

Table 5. Correlation coefficient for qEEG key performance indicators

Factor	Attention	Workload	SMR	HR	GSR	HRV	RR
Attention	1.0	0.83*	0.65*	0.88*	0.89*	0.85*	0.88*
Workload		1.0	0.66*	0.84*	0.82*	0.81*	0.84*
SMR			1.0	0.71*	0.69*	0.66*	0.70*
HR					1.0 .88*	−0.72*	0.94*
GSR					1.0	−0.78*	0.91*
HRV						1.0	0.82*
RR							1.0

Definitions as in Table 2. GSR, galvanic skin response; HR, heartrate; HRV, heartrate variability; qEEG, quantitative electroencephalography; RR, respiration rate; SMR, sensorimotor rhythm.

* $P \leq 0.05$

workload and attention metrics to be superior in female participants compared with male participants.^{8,12,15,23} Our data partially supported these trends as brain workload measures were significantly higher in male athletes, yet attention metrics were higher in female athletes ($P \leq 0.05$), (Tables 2, 3, and 4). Overall, the female athletes experienced less attention loss than male athletes throughout the functional movement tasks and had more attention capacity than male athletes overall. Previous literature suggests female participants function and learn using a variety of strategies while male participants seem to thrive in environments with structure when functioning or learning a new and/or different content.⁴⁰

Tests implementing single-leg balance tasks, similar to the ones used in the current study, have been reported to lower attention, especially when participants focus too much on the intensity of the movement or on efforts toward increasing muscle strength and/or neural recruitment.^{13,15,17,28} In addition, the alpha desynchronization was more prominent in the right hemisphere when standing on the right leg, which suggests hemispheric asymmetries are expected during single-leg postural tasks.^{13,15,18,28} The more symmetrical presentation of the brain hemispheres in women for pre- and post- motor tasks, support a trend toward women being more neutrally efficient and more focused. Such insight may help to explain sex differences regarding susceptibility to injury while supported on one leg, such as noncontact anterior cruciate tears among women.¹⁴

Further, despite having no sex differences in the pre- and post-SMR values, there were significant SMR differences overall from pre- to post-motor imagery tasks ($P \leq 0.05$). Thus, the practice of using motor imagery appears to have no sex bias, but does impact the neural template.¹⁴ Our data indicate motor imagery to be a good practice when initiating motor performance regardless of sex. How qEEG and neurophysiological data can impact biomechanical control and/or injury is yet to be fully

determined; however, these data offer promising outcomes regarding the impact motor imagery can have on the CNS.

The higher consistency of attention levels in the female participants may also indicate that Division I male athletes are less capable of adapting to new challenges, such as the different tests and/or the sequences of testing for memory, reaction time, and functional movement tasks. We performed a multitude of fairly novel functional tasks; yet, due to the common practice of exercise testing in monitoring athletic performance, the tasks could be considered relatively familiar to most athletes. It is likely the elevated workload in healthy, uninjured male participants was a neurophysiological response to make up for the lower continuity in brain attention, whereas the higher attention levels among female participants may have countered the necessity for higher brain workload activity. This may also offer insight on the impact sex has on a learning effect relative to the neurophysiological aspects of the brain/body becoming more familiar with being physically challenged or tested.

Our study is the first to identify sex differences as it relates to neurophysiological function and may have implications for identifying regulatory brain characteristics associated with healthy uninjured athletes.³² A neurological normative profile or baseline data may be warranted when monitoring athletes for training and/or rehabilitation practices.^{28,32} Overall, the current methodology appears to provide actionable, in depth, and objective information regarding sex distinctions for neurological and musculoskeletal performance capacities.

The standard neurophysiological patterns from the current qEEG and physiometric data, representing healthy uninjured athletes, clearly provided objective data to serve as a neurological benchmark to aid clinicians in making comprehensive decisions concerning an athletes' readiness to play and/or return to participation that go beyond physical outcomes, i.e., bilateral muscle testing.^{5,29,40} The findings may be

more relevant in future studies when comparing healthy athletes with those with injury or a previous condition.^{3,6,25,29} Clinicians should consider altered neurophysiological performance, good and bad, in tandem with altered biomechanical and/or reaction time tasks to be a direct indication that the brain is functioning in a regulated and/or dysregulated state.^{5,23,25,26,29}

Previous literature has associated brain asymmetries with a potential increase in the risk of injury in sport.^{14,15,23,25,26,29} Variation and adaptability in muscle and brain symmetry between left and right hemispheres are common in elite athletes due to sport-specific training, high volumes/intensities, fatigue, and skill development.²⁹ However, there is evidence to suggest that physical assessments may not be able to detect these muscle asymmetries.^{5,29} Monitoring neurophysiological outcomes, such as brain dysregulation or hemispheric asymmetry, in tandem with physical tasks may be more sensitive in identifying preceding characteristics to injury.^{23,25,29} There is evidence to suggest that fluctuating asymmetries may be related to impaired athlete biomechanical and/or overall performance.^{14,15,26,31} In conjunction with these findings, there were consistent positive correlations between multiple physiometric and biometric variables (HR, etc) related to performance and stress demands placed on the CNS and musculoskeletal systems (Table 5). Neurophysiological outcomes have a great potential in complementing musculoskeletal testing, as well as offer additional warning signs of potential dysfunction otherwise not seen by routine physical musculoskeletal tests.³⁹ Such information can be used to equip clinicians to be proactive in applying interventions targeting deficits otherwise not seen.

To date, the literature has sought to determine whether the influence of CNS asymmetries and/or brain dysregulation are independent of the functional properties of the neuromuscular parameters (Table 2).^{14,15,31} We propose qEEG neurophysiological assessments for healthy, uninjured athletes will serve to help determine brain regulatory status beyond what is possible with traditional biomechanical testing, thus transforming the way clinicians evaluate and treat athlete preparedness regarding neuromuscular function and the mitigation of injury.^{23,29,40} To date, fMRI has been a premier assessment to help identify the brain's role relative to appropriate biomechanical function and injury.^{14,15,23,31} However, fMRI analysis relies on multiple assumptions regarding the functioning properties of the brain. fMRI detects areas of increased oxygenated blood flow, which implies that the area has increased metabolic activity and brain workload requiring increased aerobic activity. These assumptions are based upon the limitations of the fMRI to assess paramagnetic properties of oxygenated versus deoxygenated hemoglobin and that the brains' blood flow is independent of the parasympathetic nervous system control. fMRI does not measure neurological activity directly, and does not account for the phenomenon of vasomotion, or the brain's capability to produce lactate under various metabolic demands, including anaerobic metabolism.^{14,23,40}

While fMRI provides valuable insight into better understanding the athletic brain, it is, by nature, limited to mostly static or restricted assessment properties.^{4,31} The confines of the fMRI are

not practical to assess athletes during dynamic activities, and therefore is not suited for a functional, biomechanical clinical setting.^{15,23,29} In contrast, traditional qEEG/EEG assessments appear to be more practical in a clinical sports medicine setting due to vastly decreased machinery demands, which are supported by decades of validation for measuring brain activity during functional cognitive and physical tasks.^{23,29,31} The current data and study procedures suggest that wireless qEEG and physiometric sensors are a practical, convenient, and rigorous alternative to current practices. Further, assessing various physical dynamic movement and cognitive tasks have less limitations with the qEEG. In addition, qEEG offers a substantially more cost-effective alternative, typically reducing expenses by approximately 75% when compared with fMRI, while also presenting distinct advantages in terms of accessibility and ecological validity. These attributes render qEEG particularly well-suited for evaluating functional brain dynamics in sport and athletic contexts.

Limitations

The qEEG neurophysiological assessments were performed on healthy, nonfatigued, uninjured, Division I athletes using musculoskeletal movements associated with sport. Fatigue factors have a high correlation with the success of performing functional movements, but we did not test athletes in a fatigued condition.^{13,15,28} In addition, we did not collect qEEG data during maximal intensities of strength and/or power activities. The physical activities were limited to controlled and previously published activities. Notwithstanding, the functional activities used in the current study did incorporate some elements of sport, such as fast reaction responses and musculoskeletal coordination.

CONCLUSION

The novel benchmark neuromeric and physiometric performance data from this work demonstrate normative brain-to-body readiness and functional capacities that can assist with assessing and/or managing brain readiness as it relates to functional performance capacities. Identifying potential pre-existing conditions associated with brain-to-body readiness may assist in establishing more refined training modalities. Our data and methodology support tandem qEEG and physiometric assessments to serve as objective comparative normative baselines. One might surmise that monitoring brain-to-body functional connections via qEEG and physiometric data will equip clinicians and athletes with information to assist in optimizing brain-to-body acuity, thus maximizing key performance indicators, such as brain workload, attention, reaction time, and abilities to enhance athlete readiness for participation and/or safe return to play. Further, the data presented and analytics collected from the qEEG, physiometrics, and physical movements appear to offer additional insight not detected by traditional neuromuscular and functional assessments. These findings establish a foundational benchmark for neurophysiological readiness in athletes, offering clinicians a robust tool for performance and rehabilitation decisions.

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