

An investigation into the utility of wearable sensor derived biofeedback on the motor control of the lumbar spine

by

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ABSTRACT

Lower back pain (LBP) is a disability that affects a large proportion of the population and treatment for this has been shifting towards a more individualized, patient-centered approach. There has been a recent uptake in the utilization and implementation of wearable sensors that can administer biofeedback in various industrial, clinical, and performance-based settings. The overall aim of this Master's thesis was to investigate how wearable sensors can be used in a sensorimotor (re)training approach, including how sensory biofeedback from wearable sensors can be used to improve measures of spinal motor control and proprioception. Two complementary research studies were completed to address this overall aim.

As a systematic review, Study #1 focused on addressing the lack of consensus surrounding wearable sensor derived biofeedback and spine motor control. The results of this review suggest that haptic/vibrotactile feedback is the most common and that it is administered in an instantaneous real-time manner within most experimental paradigms. Further, study #1 identified clear gaps within the research literature. Specifically, future research would benefit from more clarity regarding study design, and movement instructions, and explicit definitions of biofeedback parameters to enhance reproducibility.

The aim of Study #2 was to assess the acute effects of wearable sensor-derived auditory biofeedback on gross lumbar proprioception. To assess this, participants completed a target repositioning protocol, followed by a training period where they were provided with auditory feedback for two of four targets based on a percentage of their lumbar ROM. Results suggest that mid-range targets benefitted most from the acute auditory feedback training. Further, individuals with poorer repositioning abilities in the pre-training assessment showed the greatest improvements from the auditory feedback training. This suggests that auditory biofeedback training may be an effective tool to improve proprioception in those with proprioceptive deficits.

Collectively these complimentary research studies will improve the understanding surrounding the ecological utility of wearable sensor derived biofeedback in industrial, clinical, and performance settings to enhance to sensorimotor control of the lumbar region.

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REVIEW OF THE LITERATURE

1.1 Low Back Pain and Motor Control

A large motivation for the biomechanical and neuromuscular assessment of spine function is the high prevalence and incidence of low back pain (LBP) within industrialized countries. This has led researchers to investigate the complexity and adaptability of spine motor function, and the association of spine motor function with specific and non-specific lower back disorders. This section of the literature review will present the large socioeconomic burden associated with low back disorders, while also overviewing the fundamental principles governing lumbopelvic motor control.

1.1.1 An Overview of Low Back Pain

LBP is pain or discomfort in the lumbar region of the spine which can stem from a variety of causes such as muscle strains, intervertebral disc pathologies, skeletal irregularities and more (National Institute of Neurological Disorders & Stroke [NINDS], 2014). According to the World Health Organization Global Burden of Disease study done in 2015, LBP was the number one cause of lived-with disability in the world (Hurwitz *et al.*, 2018). Further, LBP was found to be the fourth leading cause of disability-adjusted life years (Hurwitz *et al.*, 2018). A systematic review by Wynne-Jones *et al.* (2014) revealed that the occurrence of work absences among the general population as a result of LBP was 15.5%. Furthermore, those who are elderly, of lower socioeconomic status, and who are fearful of physical activity are also more susceptible to the development of chronic (i.e., lasting > 3 months) LBP (Valat *et al.*, 1997). Non-specific LBP (NSLBP), making up about 90% of LBP diagnoses, is the occurrence of LBP without an identifiable contributing physical cause following medical imaging assessments (Krismer & van Telder, 2007). The treatment approach for NSLBP has historically been homogenous (i.e., one

size fits all) although there is evidence to support that there is heterogeneity in the development and presentation of LBP disorders within the NSLBP patient population (O’Sullivan, 2005). This ultimately leads to LBP persisting past the expected tissue healing time, and the evolution of neurophysiological (mal)adaptations (i.e., Hodges & Moseley, 2003), leading to the disorder becoming chronic.

1.1.2 Low Back Pain & Mobility

Typically, there are two patient sub-groups regarding mobility in LBP: 1) those who are hypomobile and 2) those who are hypermobile (O’Sullivan, 2005; van Dieën *et al.*, 2019b). The hypomobility sub-group tends to present with high levels of muscle guarding (i.e., agonist-antagonist co-activation) and a tightly controlled motor patterns (van Dieën *et al.*, 2019b). Those in the hypermobile sub-group typically adopt flexed and/or passively extended trunk postures more frequently and can experience specific flexion- or extension-pattern pain aggravation, which can coincide with abnormal levels of lumbar musculature activity (van Dieën *et al.*, 2019b). Within this hypermobile sub-group, there has been investigation into the motor patterns presented by those within this group, and the potential association of these motor patterns with the onset and recurrence of LBP. In addition to the classification of LBP subgroups on the basis of mobility, others have suggested classification schemes on the basis of postures and movement which aggravate painful sensations. Specifically, Hall (2014) reported that presentation of mechanical LBP can be divided into four groups, categorized by two back-dominant and two leg-dominant factors. One key factor for those experiencing or developing LBP are high-risk end range postures such as those observed in highly flexed or extended positions. Experiencing LBP triggers a threatening response where relief is typically sought by adopting flexed or extended

spinal positioning to alleviate their symptoms. Identifying these pain patterns in patients experiencing LBP can be useful in addressing treatment options.

When considering the LBP subcategories presented above, typically different subgroups stand to benefit from targeted therapeutic approaches. Specifically, the hypermobile sub-group benefits from proprioceptive retraining (e.g., dissociating segments), and addressing the maladaptive motor control patterns through active-movement based rehabilitation to re-gain functional mobility (van Dieën *et al.*, 2019b; O’Sullivan, 2005). In contrast, those within the hypomobile subgroup typically benefit from mobilization techniques through passive manipulation treatments (van Dieën *et al.*, 2019b). It is worth noting that the typical treatment approach(es) for each sub-group often do not take into account the other psychosocial factors that may contribute to the persistence, recurrence, and/or rehabilitation of LBP.

1.1.3 Coordination and Neuromuscular Control

As an anatomically complex series of joints, the spinal column requires refined and adaptable neuromuscular control. To facilitate this motor control, the neuromuscular system integrates afferent information within higher-order cognitive processes to generate an efferent motor response. This efferent motor response then meets inherent stability requirements while also facilitating the generation of specific postures and movements. In the control of dynamic movement, coordination concerns the spatiotemporal sequencing of multiple inter-vertebral joints and muscle groups to facilitate a given gross spine movement (Meier *et al.*, 2019). Specifically, spine coordination is executed via the central nervous system where afferent systems (sensory feedback – neural subsystem from Panjabi, 1992) and efferent systems (muscle activation – active subsystem from Panjabi, 1992) act on the passive (skeletal and ligamentous subsystems – passive subsystem from Panjabi, 1992) and produce movement using the

musculature of the spine (Hodges, 2011). Coordination impairments are commonly observed in LBP. Specifically, decreased coordination of the erector spinae during gait, decreased coordination of trunk stabilizers by increased co-activation, and decreased proprioception of the lumbopelvic region (Lamoth *et al.*, 2006; Nelson-Wong & Callaghan, 2010; O’Sullivan, 2005) have all been observed when comparing those with LBP to healthy control populations. This therefore begs the question – which part of the neuromuscular control system is compromised in LBP states to generate these apparent dysfunctions? Previous authors have suggested that the neuromuscular control system acts in a feedback control loop as goal-directed input and system state-variable information is received, muscle force is produced and adjusted online to establish a new state of the system before the feedback (Figure 1) (Reeves *et al.*, 2007). Thus, the objective of the neuromuscular control system is to maintain dynamic and static stability of the spine, as well as facilitate dynamic motor tasks like walking, while maintaining optimal spine range of motion (ROM) and function (Reeves *et al.*, 2007). Of particular interest to this thesis is the requirement for time-varying afferent feedback regarding the state of each segment along the spinal column. Including how deficiencies in this feedback can impact the neuromuscular control of spine movement, and how externally derived sensory feedback can be used to supplement this feedback loop. Research in this area has potential implications for improving the efficiency of the neuromuscular control system in those with low back disorders, or in those who are healthy aiming, to optimize control and performance of the low back.

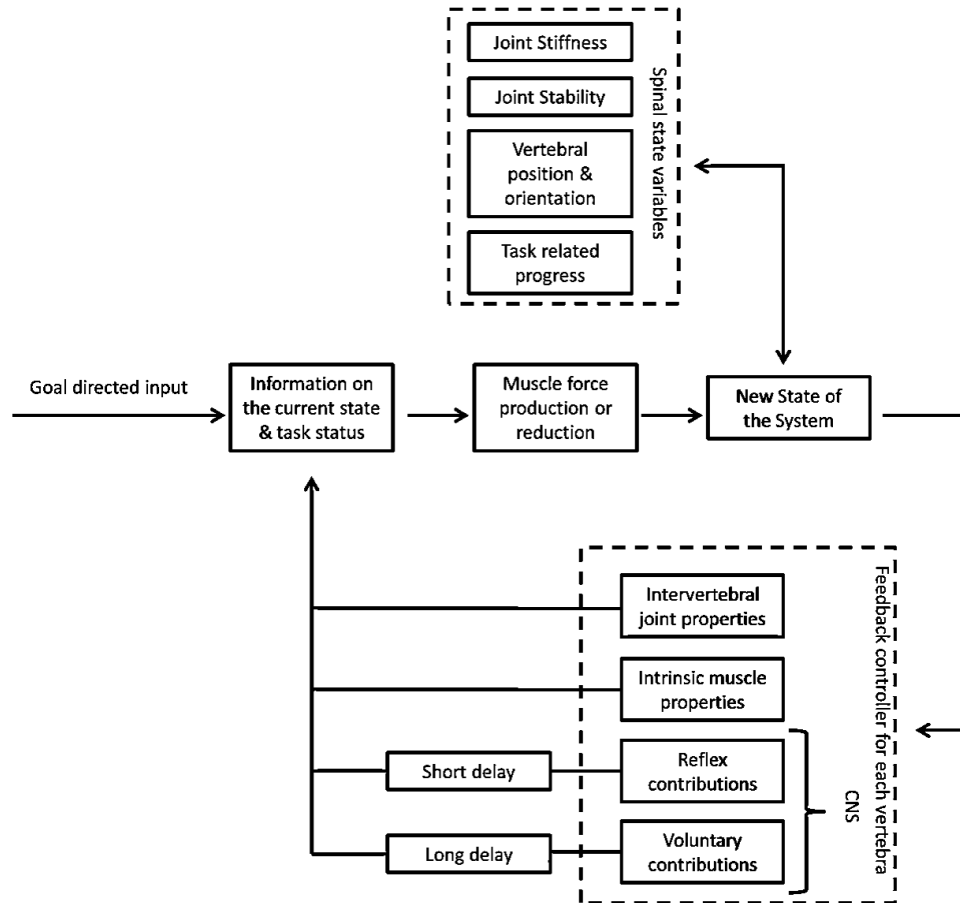


Figure 1. Components of the neuromuscular control system for the spine (adapted from: Reeves NP, Narendra KS, Cholewicki J: Spine stability: The six blind men and the elephant. *Clin Biomech (Bristol, Avon)* 2007;22:266-274.). CNS = central nervous system.

1.1.4 Proprioception

The word proprioception was proposed in 1906 by Sir Charles Sherrington by a combination of the root Latin word “proprius” meaning one’s own and “perception”, referring to proprioception as one’s intrinsic ability to perceive joint and body movements, senses of effort, force, and heaviness, as well as the body’s position in space (Han *et al.*, 2016; Proske & Gandevia, 2012). Kinesthesia is a subtype of proprioception specific to joint and body positions and movements (Bastian, 1888). Muscle receptors (e.g., muscle spindles, Golgi tendon organs), joint receptors (e.g., Ruffini-like endings) and skin receptors (e.g., Merkel cells, Meissner corpuscles, Ruffini endings, hair plexuses, free nerve endings) are the three types of receptors

that respond to different stimuli to inform on mechanical deformation and are often referred to as *kinesthetic sensors*. Based on the review by Proske & Gandevia (2012), muscle spindles are the major kinesthetic sensors, and are particularly responsible for coding changes in muscle length, and rate of change of length.

Research shows that individuals who suffer from LBP have a decreased spatial ability to detect changes in trunk position and significantly higher repositioning error during flexion repositioning tasks when compared to healthy individuals (Lee *et al.*, 2010; Newcomer *et al.*, 2000). Some mechanisms contributing to this impairment are traumatic damage of tissues, muscle fatigue, and/or over-active nociceptors, as all of these mechanisms have been shown to disrupt proprioceptive input (Taimela *et al.*, 1999; Thunberg *et al.*, 2002; van Dieën *et al.*, 2019a). Additionally, proprioception can be disrupted without any change at the level of the peripheral kinesthetic sensor. This occurs in situations such as central sensitization (i.e., allodynia or hyperalgesia, both examples of neuropathic pain), or cortical re-organization within the primary somatosensory cortex which have been shown to be associated with patients in chronic pain states (He & Kim, 2021; Zhang *et al.*, 2019), further augmenting how information from peripheral afferents are processed within the central nervous system.

1.2 *Sensory Biofeedback*

As previously mentioned, the neuromuscular control of the spine operates as a type of feedback loop, incorporating afferent feedback to inform a particular efferent motor response. Integration of proprioceptive inputs with supplemental sensory inputs such as visual, auditory, haptic, and tactile biofeedback have become a recognized area of importance for *sensorimotor (re)training*. Sensorimotor (re)training in this field of research is collectively implemented for the targeted training/rehabilitation of the sensory and motor systems as it relates to optimal

movement patterns, pain reduction, and sensorimotor rehabilitation. In general, biofeedback paradigms show promise in both performance and rehabilitation settings. Alhasan *et al.* (2017) explains that augmented biofeedback has particular utility as a training method rather than a treatment, because the intervention provides additional information about the individual's body function in order to enhance performance through changed behaviours. In general, biofeedback can be presented to the individual either in real-time (concurrent) or at a later time (terminal) (Sigrist *et al.*, 2013). The following subsections will overview specific types of sensory biofeedback, including how each has been used in the *sensorimotor (re)training* context to improve, augment, or rehabilitate the motor control of the axial skeleton.

1.2.1 *Visual Feedback*

Vision is an example of an exteroceptive sense that is specifically sensitive to light stimuli which are outside of the body, but within the body's immediate environment. Visual information is received by photosensitive receptors located within the retina of the eyes. Binocular vision facilitates the perception of depth within the visual field. In general, several methods have been employed to use visual sensory feedback to inform feedback relating to one's movements and postures. In the context of limb movements, vision is preferentially selected in the control of limbs due to the highly specialized nature of photosensitive receptors in the eyes. During early development, vision provides direct, highly specialized position and velocity sense to inform on joint and body position (Kandel *et al.*, 2013). In contrast to the limbs which are readily visible within one's field of view, one is typically unable to visualize the movement of axial structures. Therefore, visual biofeedback, in the context of providing feedback for spine/trunk movement requires the use of some visual aid so the individual can observe their movements or movement behaviour (e.g., by using a simple apparatus such as a mirror, or

through the use of streaming visual data from some other device such as a Wii Fit balance device) . Previous work has suggested that a visual feedback approach can be useful for balance and postural re-training (Alhasan *et al.*, 2017). Further, when vision is occluded in patients with LBP, their balance and postural control has been shown to decrease significantly when compared to a control cohort, as many studies have reported that patients with LBP rely more heavily on visual input compared to a healthy population (Maribo *et al.*, 2011; Mientjes & Frank, 1999; Della Volpe *et al.*, 2006; Mann *et al.*, 2010).

1.2.2 Auditory Feedback

Like vision, one's sense of hearing is an exteroceptive sense. Mechanosensitive afferents located within the inner ear are sensitive to the mechanical disturbances resulting from sound waves within our immediate environment. Time-varying changes in pitch can be interpreted to represent the direction and velocity of an object moving within our environment (e.g., *Doppler Effect*). Recently, auditory feedback has come into the spotlight in rehabilitation settings and has diverse uses in re-training opportunities between complex and simple tasks (Sigrist *et al.*, 2013). Given the wide range of potential pitches or rhythms, the structure of auditory feedback can be varied. Specifically, auditory feedback can alert individuals when they approach end-range movements (e.g., when the movement exceeds a pre-defined threshold), or can be sonified (e.g., pitch or volume change over time to match magnitude or deviation measurements) (Sigrist *et al.*, 2013). In a review done by Giggins *et al.* (2013), auditory biofeedback was used in both physiological and biomechanical feedback and showed promising results when implemented in gait and postural control re-training (Giggins *et al.*, 2013).

1.2.3 Haptic & Tactile Feedback

Haptics concerns the use of one's sense of touch to convey information. In general, tactile feedback can include sensations of pressure, stretch, and vibration which are generally used to stimulate mechanosensitive afferents embedded within the dermis and hypodermis (Beaudette, 2018). Depending on the intensity of the stimulus, mechanical stimuli delivered to the skin surface also have the capacity to activate mechanosensitive afferents located within the muscle (i.e., muscle spindles and Golgi tendon organs), or joint capsule (i.e., Ruffini-like endings). Previous work has suggested that there are two components of haptic feedback: tactile and kinesthetic (Sigrist *et al.*, 2013). Tactile feedback is typically delivered through vibrations or pressure to the skin and, as previously mentioned, kinesthesia allows for the perception of body position, and is typically coded via changes in skin stretch (Sigrist *et al.*, 2013; Proske & Gandevia, 2012).

A type of haptic feedback, vibrotactile feedback, is commonly used to guide an individual to adjust their posture to avoid prolonged periods in harmful postures which could lead to the development of LBP (Zheng & Morrell, 2010). Additionally, vibrotactile feedback can be used to simulate movement or displaced position which has been used in previous studies to demonstrate postural control differences between LBP and healthy populations (Proske & Gandevia, 2012; Claeys *et al.*, 2011). Further, low frequency and high amplitude vibrations can be administered to target muscle spindles and create the illusion of muscle lengthening, whereas high frequency, low amplitude vibrations can be administered to target skin mechanoreceptors to simulate localized skin stretch (Brumagne *et al.*, 1999; Martin *et al.*, 2015). Tactile feedback can also be administered via afferent pathways other than muscle spindles, such as through mechanoreceptors in the skin. While soft tissue artifact and skin stretch is typically a limitation

of biomechanical analyses, skin stretch occurring during spine motion may provide a source of supplementary sensory information such that attention paid at end range postures are made more prominent using passive taping and movement instructions. Typically, in lumbar spine research, strategically placed athletic tape or adhesive used to elicit tensile strain within the dermis and hypodermis (e.g., Rock tape, Kinesiotape) has been successful in limiting harmful end-ROM lumbar postures, or eliciting an active redistribution of multi-segment spine movement (Beaudette *et al.*, 2018; Pinto *et al.*, 2018).

1.3 *Spine Kinematics*

The following subsections will introduce and discuss common measures of spine motor control related to spine movement kinematics. These are important when considering the spine neuromuscular control system discussed previously (Figure 1), as motion capture is a fundamental component of motion analysis and provides approximations of skeletal movement, as well as providing biomechanically relevant biofeedback. As such, the following subsections will review methods for 2D and 3D spine motion capture modalities and related objective outcomes for spine movement performance and/or quality of movement.

1.3.1 *Laboratory Methods*

The majority of the literature regarding the assessment of spine kinematics utilizes laboratory-based equipment. In large part, this equipment is costly, and requires specialized domain knowledge to facilitate proper use (Goncharow, 2021). Generally, spine motor control can be measured holistically through assessment of spine position, orientation, externally applied forces, and trunk muscle activation profiles (Reeves *et al.*, 2007). To facilitate these measurements, three laboratory methods are commonly utilized to capture these data: 1) optical motion capture to observe movements of the body (kinematics), 2) using strain gauges, and

centre-of-pressure measurements to observe the forces that act on said body segments (kinetics), and 3) electromyography to evaluate the muscle activation for said movements (Beaudette, 2018). Generally, these streams of raw time-varying data, common in many biomechanics labs, are used to inform processed measures of spine movement performance and quality. The following subsections will provide an overview of common measures of spine movement quality obtained using the raw data streams noted above.

1.3.2 Discrete Measures of Spine Movement Quality

Discrete measures include metrics taken to represent the behaviour (e.g., pose) of the spine at a single instant in time. In most cases these measures are very easy to interpret and can be obtained from a raw time-series with minimal computational demand, thereby promoting their use in a variety of clinical settings. Discrete measures of spine movement include lumbar (trunk) ROM values, angular velocity, or acceleration values at different points in a movement (Callaghan *et al.*, 1999) or presented as computed maxima, minima, or mean values. In general, discrete measures can be limited in their ability to measure spine movement quality given that they neglect large amounts of time varying data. Despite this, researchers and clinicians alike have opted to use discrete measures as they are easily understandable, thereby improving their use in a clinical setting where communication with a client is paramount. While these measures have clear benefits in computational simplicity, they often lack the ability to represent important motor control phenomena related to movement variability and inter-joint coordination, thereby overlooking an important part of understanding multisegmented movement quality, including any potential mechanisms of injury (Panjabi, 1992) and motor learning (Hamill *et al.*, 2012). Given this, more sophisticated measures of spine function, rooted in dynamical systems theory (DST), have been used to estimate spine motor function.

1.3.3 Dynamical Systems Measures of Spine Movement Quality

Many fundamental concepts within DST relate back to the original Degrees of Freedom Problem post by Nicolai Bernstein (1967). Given the especially high anatomical complexity of the human body, there is need for coordinative structures to optimize and simplify complex multi-segment movement. In a motor control context, the term *coordination* concerns the selective spatiotemporal activation of specific degrees of freedom (i.e., joints, muscles, etc.), such that their united activation results in a smooth, organized motor activity (Weiss, 1941). DST states that there are intricate communications between subsystems and that self-organized development of movement patterns emerge given the specific demands of a task (i.e., order parameters) (Robertson *et al.*, 2014). DST explains that the number of biomechanical degrees of freedom changes as one develops (or loses) coordination, a point that reflects closely with the Bernstein perspective (Glazier *et al.*, 2003). Therefore, it is important to consider dynamic, or continuous, measures of spine movement quality as these provide insight to the processes used to achieve coordination of the spine throughout a dynamic movement. Dynamic systems measurements allow for a full movement profile for the individual, which in turn can provide information about injury mechanisms and biomechanical insufficiencies which may be contributing to LBP as specific movement time points (Graham *et al.*, 2015). There are many examples of measures based on DST including those designed to estimate coordination patterns, coordinative variability, and dynamic stability (Hamill *et al.*, 2012). According to Reeves *et al.* (2007), a common method for quantifying the dynamic stability of the spine is to use a non-linear time series analysis. Trunk control and stability can be measured using a maximum finite-time Lyapunov exponent by quantifying the neuromuscular system response to small disruptions or perturbations during repetitive, dynamic tasks (Beaudette *et al.*, 2014; Beange, 2019). Using

these data, information can be gathered and quantified regarding control changes associated with LBP, clinical stability, and clinical intervention (Beange, 2019). Recently, it has been demonstrated that these data can be collected with wearable sensors (Beange *et al.*, 2019).

1.4 *Wearable Sensors*

As noted previously, there are many fundamental disadvantages to the use of conventional laboratory equipment in ecologically relevant scenarios. Recently, there has been considerable improvements made in the design and implementation of wearable sensors aimed at capturing time-varying kinematic data. The following subsections reviews some of the most common wearable sensors implemented in recent research studies, including their potential utility in a clinical setting to evaluate spine movement and/or to administer sensory biofeedback.

1.4.1 *Types of Wearable Sensors*

According to a systematic review done by Papi *et al.* (2017), inertial measurement units (IMUs) are the most commonly used wearable sensor, although others such as electrogoniometers, strain-gauge based sensors, and piezoresistive sensors are also observed (Papi *et al.*, 2017). IMUs typically include a combination of accelerometers, gyroscopes, and magnetometers, which measure body movements based on rate of change of velocity, rate of change of angular motion, and relative orientation with respect to earth's magnetic field, respectively (Porciuncula *et al.*, 2018). Wearable IMUs have been paired with mobile-based applications to provide real-time or terminal biofeedback (Sigrist *et al.*, 2013). An example of wearable biofeedback sensors include the commercially available UPRIGHT® sensor (Upright Technologies Ltd., Yahud, Israel) which monitors the wearers posture and provides vibration cues for the user to alter their posture when a slouched posture is detected (measured by body tilt angle). Preliminary studies have shown this device can improve postural alignment in

Parkinson's disease patients and improve postural awareness of the neck and back as well as well-being in healthy young adults (Stuart *et al.*, 2019; Harvey *et al.*, 2020).

1.4.2 Clinical Utility and Recent Uptake

Recently, there has been considerable interest in how to apply the laboratory-style methods of measuring and monitoring posture/movement, in a more ecologically relevant setting (i.e., clinic, workplace, etc.). This has led to the integration of wearable sensors into clinical and professional settings and a plethora of academic research. In a clinical setting, it is very uncommon to see the research laboratory-scale equipment (as discussed previously) for assessing spine kinematics. The usual assessment of movement quality is performed visually by professionals and the reliability has been proven to be low (Dankaerts *et al.*, 2006). Further, clinic assessments also rely on reporting in the form of questionnaires, which introduces subjectivity to the treatment. Questionnaires can be useful for understanding patient attitudes towards movement and their condition; however, objective movement assessment has enhanced reliability (Cook *et al.*, 2006). There has been a disconnect between the objective measures collected from laboratory settings to their usability in clinical settings. Wearable sensors may represent a means for bridging this gap, as they are an affordable and practical way to incorporate objective data, typically gathered from the laboratory, into a clinical setting (Papi *et al.*, 2017). Further, the data derived from such sensors, if accurate, can be used to inform sensory biofeedback to both (1) increase the reach of an attending clinician/coach and (2) accelerate rehabilitation and performance-related initiatives.

1.4.3 Validity and Accuracy

For a novel device to have any clinical utility, the device must be of acceptable accuracy and precision to detect clinically meaningful changes. Even before wearable sensors began to

make their place in professional practice or everyday use from the public, professionals were apprehensive about the validity and accuracy of the devices both in ideal and uncontrolled environments (Ricci *et al.*, 2016). A systematic review done by Simpson *et al.* (2019) that investigated the role of wearable sensors in spinal posture analysis reported that there is a very high accuracy rate across systems with error rates less than two degrees. A major limitation to the accuracy and validity of wearable sensors in uncontrolled environments is that there is generally some degree of anatomical knowledge required for instrumentation, which may be affected in use by the general population. Further, some wearable sensors can be affected by environmental noise related to disruptions to a local magnetic field or sensor drift (Goncharow, 2021), which can affect pose estimates derived from IMU sensors.

1.4.4 Future Directions & Gaps in Research

Given the recent implementation and utilization of wearable sensors that can administer biofeedback in clinical, professional, and everyday settings, there was surge of research attempting to validate the usage of such sensors against conventional laboratory gold-standards. LBP is a disability that affects a large proportion of the population and recently the treatment direction has been shifting to a more individualized treatment approach. Given the research to support that wearables are valid and reliable, and currently being used in various settings, this lays the framework to investigate how wearable sensors can be used in a sensorimotor (re)training approach. This can include how sensory biofeedback from wearable sensors can be used to improve measures of spinal motor control and proprioception, and the potential utility of such approaches in clinical settings. Given this the following gaps have been identified which will be used to inform the purpose(s) and hypotheses for this MSc thesis.

First, given the lack of consensus surrounding wearable sensor derived biofeedback and spine motor control, there is a clear need to review previous research to understand any potential benefits associated with (1) specific wearable sensor types (i.e., raw data streams) and locations, (2) specific processed outcome measures, and (3) specific sensory biofeedback subtypes (i.e., visual, auditory, haptic). This will both identify prevailing trends and gaps within the research literature and inform future research related to wearable sensor derived biofeedback for sensorimotor (re)training paradigms, which have potential clinical utility.

Second, it is currently unclear how wearable sensor derived biofeedback may be used to improve spine proprioception. Proprioceptive deficits are present in a variety of lower back disorders, and it is possible that unaffected afferent (i.e., auditory) channels may be particularly useful in a sensorimotor (re)training context to improve lumbar proprioception and to avoid future injury. Novel research is required to understand if acute effects from a sensorimotor retraining paradigm are present, and if these effects constitute a proprioceptive benefit.

Given the two gaps identified above, this MSc thesis has been divided into two complimentary research studies. The first constitutes a systematic review of the literature relating to wearable sensor-derived biofeedback and spine motor control. The second constitutes an original article aimed to evaluate the acute effects of wearable sensor derived auditory biofeedback on lumbar spine proprioception.

1.4.5 Purpose and Hypotheses

The purpose and hypothesis statements for each respective research project of this MSc thesis are noted below.

Purpose # 1 - Examine the types of wearable sensor derived biofeedback currently being employed to explore and optimize spine posture and motor function biomechanics in both basic and applied research domains.

Hypothesis #1 - The types of data currently being used to promote neuromuscular adaptations gained by the use of biofeedback will be varied; however, the findings of this systematic review will synthesize data across multiple scientific domains that are using biofeedback as a research and clinical modality to improve spine motor function and optimize the use of wearable sensors to provide real-time biofeedback regarding spine posture and movement.

Purpose #2 - Explore the potential utility of wearable sensor derived auditory biofeedback on the proprioception of the lumbar spine. Specifically, comparing the individual's ability to reposition the lumbar spine at pre-determined target angles before and after a single training session with wearable sensor derived auditory biofeedback.

Hypothesis #2 - Auditory biofeedback training will be effective at acutely improving accuracy and precision of lumbar spine sagittal plane repositioning.

CHAPTER II – STUDY #1: WEARABLE TECHNOLOGY DERIVED BIOFEEDBACK TO MODULATE SPINE MOTOR CONTROL: A SYSTEMATIC REVIEW

2.1 Introduction

Low back pain (LBP) is the leading cause of lived-with disability and is the most common musculoskeletal dysfunction globally (Hurwitz *et al.*, 2018; Wu *et al.*, 2020). Further, LBP is the number one cause of activity limitation (Wu *et al.*, 2020), dramatically limiting one's quality of life. Despite the major global public issue LBP continues to pose, there remains limited understanding about the underlying pathologies that may contribute to the development and persistence of LBP, particularly non-specific LBP (NSLBP) which does not have any underlying structural basis, or prevailing treatment option. NSLBP is thought to be multifaceted in nature, with different underlying mechanisms that can be psychosocial and mechanical (O'Sullivan 2005; Papi *et al.*, 2017). Research surrounding LBP has focused on the neuromuscular deficiencies presenting in individuals suffering from LBP, specifically compromised motor control patterns. LBP patients demonstrate reduced spatial tactile acuity (Luomajoki & Moseley, 2009) and a decreased ability to detect changes in trunk position and significantly higher trunk flexion repositioning error (i.e., both passive and active repositioning) compared to healthy individuals (Lee *et al.*, 2010; Newcomer *et al.*, 2000). Additionally, balance detriments have been exhibited in the LBP population compared to healthy controls, especially when asked to perform balance tasks with their eyes closed, further indicating impaired proprioception and increased reliance on visual feedback (Maribo *et al.*, 2011; Mientjes & Frank, 1999; Della Volpe *et al.*, 2006; Mann *et al.*, 2010).

Spine posture and movement has historically been monitored using optical motion capture systems that use kinematic markers which can be affixed to the skin or rigid bodies.

These systems can be cumbersome and have limited utility in a clinical setting due to factors such as cost, and time and training required to ensure proper function. Additionally, the use of these systems require extensive anatomical knowledge thereby dramatically limiting the ecological utility of such systems. As a result of this, there has been a recent uptake in the use of wearable sensors to facilitate the tracking of human kinematic variables in a clinical setting. Simpson *et al.* (2019) reported that wearable sensors have good accuracy for assessing spinal posture. Further, according to systematic reviews done by Simpson *et al.* (2019) and Papi *et al.* (2017), inertial measurement units (IMUs) are the most common type of wearable sensor used to monitor spine movement. In addition to monitoring spine movement, IMUs have been paired with mobile-based applications to provide biofeedback to the user in order to allow them to adjust their posture and/or movement patterns (Sigrist *et al.*, 2013).

There are different types of biofeedback that can be administered to an individual such as visual, auditory, and haptic (i.e., tactile). Biofeedback can be presented to the user in real-time while the movement or posture is occurring, or at a later time (Sigrist *et al.*, 2013). Due to the accessibility of wearable sensors to monitor spine posture and movement, wearable sensor mediated-biofeedback can be introduced in both clinical and real-world settings for everyday use, such as the UPRIGHT® device (Upright Technologies Ltd., Yahud, Israel). The importance of introducing this training technique and optimizing real-time biofeedback administered by a wearable sensor is to allow users to refine motor strategies based on reliable kinematic data streams. In particular, wearable sensor mediated biofeedback may have utility in alerting users to sustained high-risk postures, to reinforce specific motor coordination patterns, or to complete proprioceptive training.

The purpose of this systematic review is to examine the types of wearable sensor derived sensory biofeedback modalities currently being employed to explore and optimize spine posture and motor function biomechanics in both basic and applied research domains. Further, this study will explore the types of data being used to promote neuromuscular adaptations gained by the use of biofeedback, and to comment on the utility and practicality of wearable sensors and biofeedback. Specific biological outcome measures regarding the wearable sensor-mediated biofeedback can improve or alter a clinically relevant outcome (e.g., spine posture or ROM) are explored. The findings of this systematic review aim to synthesize data across multiple scientific domains (engineering, computer science, neuroscience, rehabilitation medicine) that are using biofeedback as a research and clinical modality to improve spine motor function and optimize the use of wearable sensors to provide real-time biofeedback regarding spine posture and movement.

2.2 Methods

For this systematic review databases were queried between the months of August 2020 and September 2020. Those included on the research team for this work included Aurora Battis (AB), Jarrett Norrie (JN), Hannah McMaster (HM), and Dr. Shawn Beaudette (SB). The roles of each member of the research team in the search and subsequent evaluation processes are summarized below.

2.2.1 Search Strategy

Five databases were searched including: Embase, PubMed, Scopus, Cochrane, and IEEEExplore. Relevant spelling variations, synonyms and alternative terms were included and modified as deemed appropriate by the researchers for each database. Sensors, outcomes, biofeedback, and spine were used as general areas to identify a comprehensive list of articles that

encompassed the scope of this review, and the specific search terms for each can be seen in Table 1. The reference lists of relevant articles were screened for appropriate titles that may have been missed in the electronic searches. Search results from each database were exported in an ASCII format, and compiled using Microsoft Excel for further review and removal of duplicates. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for this systematic review, and the review process is summarized in Figure 2.

Table 1. Search terms used.

General Area	Specific Search Terms
Sensors	Sensor OR inertia OR accelerometer OR gyroscope OR goniometer OR wearable OR portable OR movable OR worn OR ambulatory OR non-invasive OR wireless AND
Outcomes	kinetic OR kinematic OR motion OR movement OR assessment OR joint OR frontal OR sagittal OR transverse OR twist OR flexion OR extension OR lateral bending AND
Biofeedback	biofeedback OR feedback OR sensory OR tactile OR vibration OR touch OR haptic OR auditory OR sound OR visual OR sensorimotor AND
Spine	Spine OR spinal OR back OR vertebra

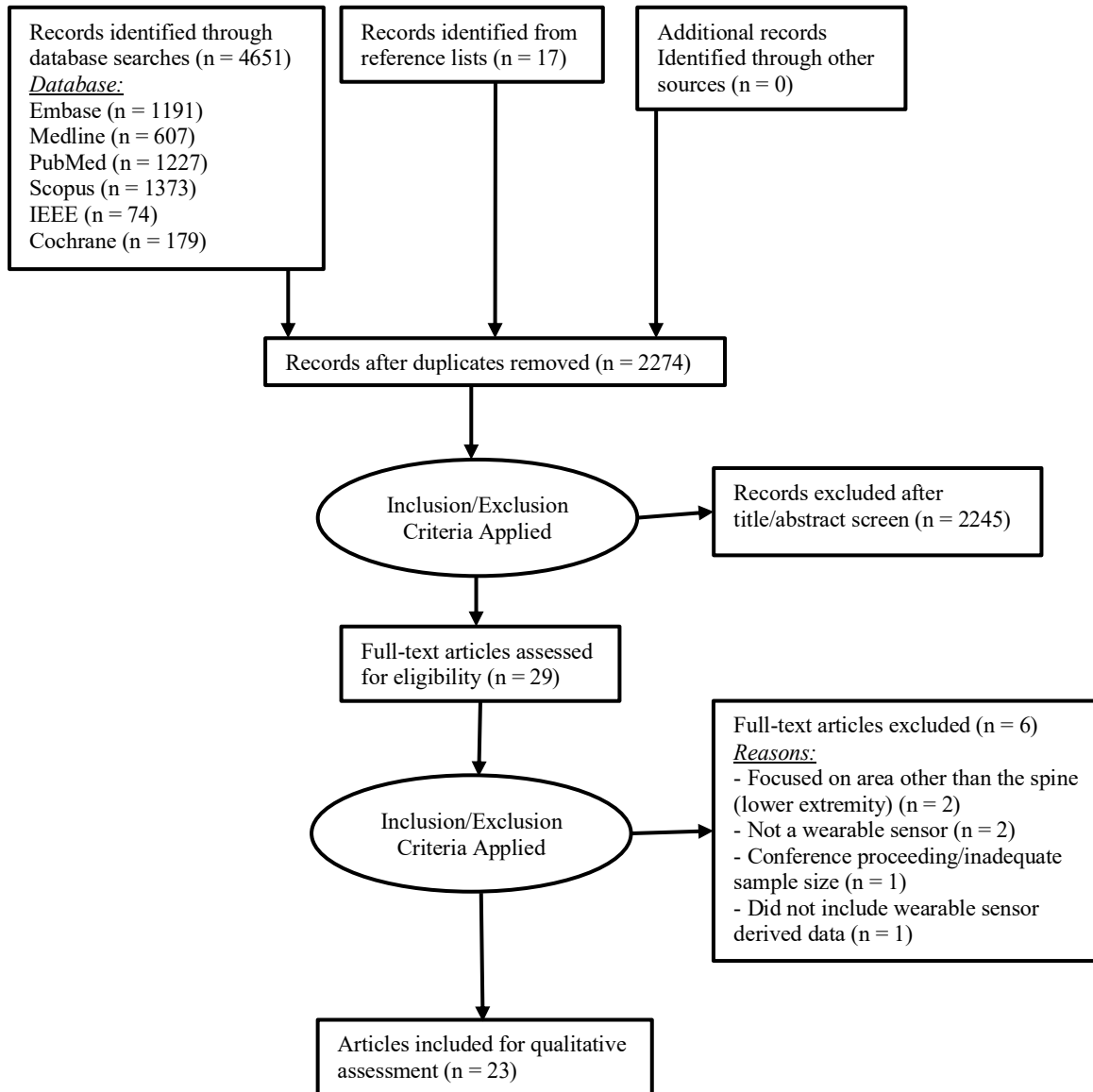


Figure 2. PRISMA chart outlining the review process.

2.2.2 Inclusion and Exclusion Criteria

Duplicate studies were removed and a primary screening of titles that were retrieved from each database was completed by one reviewer (AB). Following the primary screening, abstracts of potential articles were assessed by one reviewer (AB) with secondary assessment by a second reviewer if necessary (JN). Following the title and abstract triage, two reviewers (AB and JN) reviewed the full text of potential articles against the eligibility criteria to ensure the articles satisfied the requirements for this systematic review. Articles were included if they were published in English, assessed the spine/trunk, used wearable (wireless) technologies, implemented sensory biofeedback, were peer-reviewed, involved an adult population (>18 y/o), presented original data, and were published on or after 1980. Articles were excluded if they were a review, pilot or case-study, book, or book chapter, used non-wearable devices, described potential technologies not validated on human subjects, did not assess motion of the spine/trunk, and featured wearable technologies that are classified as robotic or exoskeletons.

2.2.3 Quality Appraisal and Data Extraction

A quality appraisal checklist was adapted from Papi *et al.* (2017) and was used to assess the quality of articles based on items such as external validity, potential bias in outcomes and protocol reporting specifically evaluating outcome evaluation and use of the technologies. The quality appraisal checklist has 22 items (Table 2) and each item is rated as zero (no detail or comment), one (limited detail) or two (good detail). Each paper was evaluated and scored based on the quality appraisal checklist by two researchers (AB and JN) and any discrepancies on scores (> 1 point separation between reviewers) were settled by a third researcher (SB). Mean results are depicted throughout the manuscript.

A customized data extraction form was developed to identify relevant points for each full text included for review. These key relevant points included study aims and design, sample population, wearable sensor type and instrumentation, kinematic data obtained, biofeedback type, biofeedback thresholds and triggers, and conclusions and limitations (Table 4). Data extraction was completed by two researchers (AB and HM) in consultation with a third researcher (SB).

2.3 Results

2.3.1 Articles Selection

The search identified 4651 potentially relevant articles, with 17 articles identified from the references of related articles and hand searches. 2274 articles remained for consideration after duplicates were removed. Following the screening of titles and abstract for inclusion and exclusion criteria, 29 full text articles were retrieved for further review. Four additional full text articles were then excluded due to the lack of association with the spine ($n = 2$), or the lack of wearable sensor derived data ($n = 3$), and inadequate sample size ($n = 1$). The final number of articles included for full review was 23. The article selection process and justifications for full text exclusion are shown in Figure 2.

2.3.2 Quality of Reviewed Articles

The overall quality of papers was rated using an adapted scale derived from Papi *et al.*, (2017) and Ratcliffe *et al.*, (2014). The questions included in the quality appraisal are presented in Table 2. Each item of the quality appraisal was assessed on a three-point scale (0 = No detail, 1 = limited detail, 2 = good detail). Of the 23 articles selected for full review, one paper was rated at low quality, 13 were rated at medium quality, and nine were rated at high quality. Itemized scores for each paper can be found in Table 3. Sample sizes were poorly justified, as

demonstrated by low scoring for a majority (16/23) of papers on item six. 10/23 studies included demonstrated average or below average reporting on standardization of movement instructions, as well as signal handling and processing (14/23). A majority of studies were rated as high quality on reporting the main objectives of the research (14/23), main findings of the research (21/23) and appropriate statistical tests used (18/23). Almost all studies reported high detail regarding the type (20/23) and implementation of biofeedback (16/23).

Table 2. Quality appraisal questions.

QUALITY INDEX ITEM
1. Were the research objectives or aims clearly stated?
2. Was the study design clearly described?
3. Was the study population adequately described?
4. Were the eligibility criteria specified?
5. Was the sampling methodology appropriately described?
6. Was the sample size justified?
7. Did the method description enable accurate replication of the measurement procedures?
8. Was the participants' assessor described (e.g., expertise)?
9. Was a system for standardizing movement instructions reported?
10. Was equipment design and setup clearly described?
11. Were sensor locations accurately and clearly described?
12. Was the sensor attachment method clearly described?
13. Were the spine segments analyzed clearly described?
14. Was the signal/data handling described?
15. Were the main outcomes measured, and the related calculations (if applicable) clearly described?
16. Was the type of biofeedback clearly described?
17. Was the participant instructed how to respond to the biofeedback?
18. Were the main findings of the study stated?
19. Were the statistical tests appropriate?
20. Were the limitations of the study clearly described?

Table 3. Quality assessments of included articles.

Quality Index Item	Afzal et. al, 2015	Afzal et al., 2018	Bao et al., 2018	Breen, Nisar & ÓLaighin, 2009	Brodbeck et al., 2009	Cerqueira, Ferreira Da Silva & Santos, 2020	Chiari et al., 2005	Franco et. al, 2012
1	2	1	1.5	1	1.5	2	1	1
2	2	1.5	2	1	2	2	1	1
3	2	2	2	0.5	0.5	1	1	1.5
4	1.5	1	2	0	0	0	0	1
5	1.5	1	2	1	1.5	1.5	2	2
6	1.5	0.5	1.5	0	0	0	0	0
7	1.5	2	2	1.5	1	1.5	1.5	1
8	0.5	0	2	0	2	1.5	0	0.5
9	0.5	0.5	1	0.5	0	2	1	0.5
10	1.5	2	1	1	1.5	2	1	1
11	0.5	1.5	1	2	1	1.5	1.5	1.5
12	1.5	1.5	2	0	2	2	1	2
13	0.5	0	1.5	1.5	1	1	1	1.5
14	1.5	1	0.5	0.5	0.5	1	1.5	2
15	2	2	2	2	1	2	1.5	2
16	1.5	1.5	2	2	2	2	2	2
17	0.5	2	2	1	1.5	1	2	1.5
18	2	2	2	2	1.5	1.5	2	1.5
19	2	2	2	0	0.5	2	2	2
20	2	1	2	0.5	0	0	0.5	1
Total Score (/40)	28.5	26	34	18	21	27.5	23.5	26.5
Percentage	71.25	65	85	45	52.5	68.75	58.75	66.25
Quality Category	H	M	H	M	M	H	M	M

Table 3 (cont'd). Quality assessment of included articles

Quality Index Item	Gopalai et al., 2011	Kent, Laird & Haines, 2015	Kentala et al., 2003	Matheve et al., 2018	Nanhoe-Mahabier et al., 2012	O'Sullivan et. al, 2013	Ribeiro et al., 2020	Sienko et. al, 2010
1	0	2	2	2	1	1.5	2	0.5
2	1.5	2	2	2	2	2	2	2
3	1	2	2	2	2	2	2	1.5
4	1.5	2	2	2	1.5	2	2	1
5	2	1	1	0	0	1.5	0	2
6	0	2	0	2	0	0	2	1.5
7	2	2	1.5	2	2	2	1	2
8	0	2	0	0	0	0	1	0.5
9	1	2	2	2	1.5	2	0	2
10	1.5	2	1.5	2	0	2	0	2
11	0.5	1.5	1.5	2	1.5	2	0.5	2
12	1	2	1	0	1.5	0.5	1	1
13	0	2	0.5	2	0.5	1.5	0	1
14	2	1	1	0	0.5	0.5	0	1.5
15	2	2	2	1.5	2	2	1.5	2
16	2	1.5	2	2	2	2	1.5	2
17	2	2	1.5	2	2	1.5	1.5	1.5
18	1.5	2	2	2	2	2	1.5	2
19	2	2	2	2	2	2	2	2
20	0.5	2	0	2	1	2	1	0
Total Score (/40)	24	37	27.5	31.5	25	31	22.5	30
Percentage	60	92.5	68.75	78.75	62.5	77.5	56.25	75
Quality Category	M	H	H	H	M	H	M	H

Table 3 (cont'd). Quality assessment of included articles

Quality Index Item	Sienco et. al, 2013	Stollenwerk et al., 2019	Stredova et al., 2017	Vignais et al., 2012	Volpe, Giantin, Fasano, 2014	Wong & Wong, 2008	Yoon et. al, 2015
1	2	1	0.5	2	2	2	2
2	1.5	0	0.5	2	2	0.5	2
3	2	0	1.5	2	2	1.5	0
4	0.5	0	1	0	2	0.5	2
5	1	1.5	0	2	1.5	1.5	1
6	0	0	0	0	0	0	2
7	1.5	1	0.5	2	1.5	1	1.5
8	2	1	0	0	0	0	0
9	2	0.5	0	1.5	0	0	1.5
10	1	1.5	1	2	0.5	2	2
11	1	0	1.5	1.5	1.5	2	1.5
12	0	2	0.5	1.5	0.5	1.5	0
13	0.5	0	1.5	0.5	2	2	1.5
14	2	2	0	0	0	2	1.5
15	2	2	1	2	2	2	1.5
16	2	0	0.5	2	0.5	1.5	2
17	1.5	0	0	1.5	0	0.5	1.5
18	1	1	1.5	2	2	1.5	2
19	1	2	0	0.5	2	2	2
20	1.5	1	0	1.5	2	0	1.5
Total Score (/40)	26	16.5	11.5	26.5	24	24	29
Percentage	65	41.25	28.75	66.25	60	60	72.5
Quality Category	M	M	L	M	M	M	H

2.3.3 Descriptive Aspects of Reviewed Articles

Of the articles reviewed, 10/23 examined a healthy participant population. 9/23 articles reported a clinical population, including patients with LBP, Parkinson's disease, or other vestibular deficits. Two articles assessed both a healthy and a clinical patient population and two did not report on their patient populations, instead referring to them as "users" (Table 4).

Most (21/23) of the articles reviewed utilized inertial sensors (i.e., IMUs, accelerometers, gyroscopes), with one of those studies also incorporating EMG data. One article assessed posture through a strain-based sensor. Finally, one article reported use of a wearable postural stabilizer but failed to provide adequate information regarding the sensor type, and function.

The primary outcome of 8/23 articles focused on joint angles (i.e., lumbar spine, hip, neck). 14/23 articles reported on segment orientations (i.e., body tilt relating to the thorax and pelvis, postural control). 1/23 articles included outcomes related to muscle activation through EMG. Additionally, 1/23 articles primary outcome measure was static posturography following training with the wearable postural stabilizer.

10/23 articles reviewed provided only haptic/vibrotactile feedback, 5/23 provided only visual feedback, and 4/23 provided only auditory feedback. 2/23 utilized both auditory and visual feedback, 1/23 utilized both vibrotactile and visual feedback, and 1/23 used all three types of feedback.

A majority (16/23) of the articles reported biofeedback to be administered in an instantaneous "online" manner (i.e., exceeding a predefined threshold). 3/23 articles reported providing continuous "online" biofeedback which was always linked with visual biofeedback. Additionally, 2/23 articles reported administering biofeedback in two different ways, with visual always being continuous "online" and the other (haptic/vibrotactile and auditory) being provided

instantaneously “online”. 2/23 articles did not report the biofeedback triggers and timing. No articles utilized a delayed “offline” technique.

Table 4. Data extraction table.

Reference	Aims	Sample	Sensor Type	Sensor Location	Processed Sensor Outcome	Biofeedback Trigger	Biofeedback Type	Conclusions	Limitations
Afzal et. al, 2015	Investigate whether a haptic feedback system is effective in reducing postural sway in young healthy subjects and in improving mean velocity displacement and planar deviation in stroke patients	Young healthy and clinical (stroke patients)	Smartphone with accelerometer and magnetometer)	1 sensor (attached to waist via leather belt)	Projection of trunk tilt; Mean Velocity Displacement; Planar Deviation; and the ML and AP Trajectories	When a subject exerted any force in the Yp axis of the haptic device	Haptic	Our kinesthetic haptic feedback system was effective to reduce postural sway in young healthy subjects regardless of posture and the condition of the substrate (the ground) and to improve MVD and PD in stroke patients who assumed the Romberg stance	Small sample size; relatively slow update rate; simplified estimation of trunk tilt projection in upright posture which cannot include the possible effects of motion at hip; lack of measurement of changes in dynamic balance; and no long-term follow-up
Afzal et al., 2018	Assess the efficacy of using a wearable biofeedback device that generates light-touch biofeedback in aiding balance maintenance in stable and unstable conditions	Healthy young individuals	IMU (on-board inertial measurement unit)	1 sensor (4 RW's) worn on back (2 shoulder straps 1 waist strap)	Torso tilt angle in mediolateral plane	$\pm 1^\circ$ about the vertical	Haptic	Experimental trials supported the feasibility of the system as a balance training aid	Small sample size (7); heavy weight of sensor backpack can be uncomfortable for subjects; only provides balance cues in ML direction; study didn't identify balance recovery effects from added weight of sensor backpack
Bao et al., 2018	Assess the efficacy of long-term balance training with and without sensory augmentation among community-dwelling healthy older adults.	Community dwelling older (65-85 y/o) adults	IMU (iphone)	1 sensor (L4/L5 region) + 4 tactors (navel, lumbar spine, L/R sides of torso)	Trunk acceleration/displacement (step-outs?)	The tilt angle plus one half times the tilt angular rate for Categories 1, 2, 4 and 5, and as the tilt angle for Category 3 exercises	Vibrotactile	The findings of this study support the use of sensory augmentation devices by community-dwelling healthy older adults as balance rehabilitation tools, and indicate feasibility of telerehabilitation therapy with reduced input from clinicians.	First, vibrotactile SA was only provided during a subset of exercises under the gait category; Second, correctness of exercise performance was not monitored during training; Third, small sample size; Finally, the information provided to the physical therapist by the smart phone balance trainer was limited to the number of step-outs in the six repetitions and the stability perception ratings from the participants.
Breen, Nisar & O'Laighin, 2009	Comparing the efficacy of using a wearable sensor that detects bad cervical posture	Regular computer users (no history of neck/back pain)	Accelerometer	1 sensor (C7)	Percentage of time spent outside cervical posture threshold with and without biofeedback	Visual feedback continuous; auditory outside range of -5° to 10°	Auditory and visual	The results from data collected during this study suggest that participants were able to maintain better cervical posture when	Did not take lumbar or thoracic regions into account; cervical movement only monitored in sagittal plane

	in healthy subjects for reducing percentage of time spent in bad cervical posture at computer with and without biofeedback							working with the biofeedback system.	
Brodbeck et al., 2009	Address limitations of current conservative therapy, by automatically monitoring movement exercises in real time, generating a motivating, game-like visual feedback, and storing patients' performance data for later assessment.	Clinical (chronic LBP or undergone back surgery)	Inertial sensor modules	2 sensors (T12/L1 and L5/S1)	Mobilization and stabilization exercises: the ratio of number of times that the range of motion limit was reached to the total number of attempts of a particular performance of the mobilizing exercise; Game exercises: The ratio of caught vs. missed balls is displayed as a score, and the final score is recorded as the success level of this exercise in the patients' therapy history.; Clinical evaluation: subjective satisfaction of system questionnaire	Ranges determined by therapists (adjustable range enabling therapist to set difficulty for an exercise unique to each patient)	Visual and ambient (lightbulb)	The abstract visual feedback that we designed was considered helpful. Ambient feedback in the form of the Lightbulb proved to be a very useful addition to the computer screen in a real-life therapy setting.	N/A
Cerqueira, Ferreira Da Silva & Santos, 2020	Aims to empower operators with posture awareness and provide objective data to ergonomists	5 subjects ("users")	IMU (3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer)	4 sensors (T4, each upper arm, back of head)	Ergonomic risk level (each sample is converted from an analog angular value to a state)	When user exceeds recommended time outside threshold (individualized thresholds)	Haptic	The results showed that providing real-time biofeedback to the subject improves posture awareness, and has a significant impact on reducing the ergonomic risk, with reductions of up to 39.8% of the time spent in hazard postures.	N/A
Chiari et al., 2005	Describe the architecture and the functioning principle of this ABF system, and examine if that ABF benefits normal, healthy subjects most when sensory information is partly compromised	Normal, healthy individuals	Linear uniaxial accelerometer	1 sensor (L5 region)	Trunk acceleration	Moving outside of the 'reference region' (defined as a function of an individuals height)	Auditory	This acoustic information helped subjects reduce postural sway, especially when visual and sensory information were compromised by eye closure and stance on foam.	N/A

Franco et al., 2012	To assess the effectiveness of a system that monitors the trunk angular evolution during bipedal stance and helps the user to improve balance through a configurable and integrated auditory-biofeedback loop	Young healthy individuals	IMU sensors on smartphone (accelerometer, gyroscope, magnetometer)	3 sensors on smartphone mounted on L5	(1) the root mean square trunk tilt in the ML and AP directions (RMS in degree), (2) the energy of the angulation signal in the ML and AP directions (in deg), (3) the 95% spectral edge frequency of the trunk tilt in the ML and AP directions (SEF95 in Hz), and (4) the duration of instability expressed as the time elapsed outside the DZ (error time in s)	ML trunk sway moving outside the deadzone (set to 1°)	Audio	Healthy individuals were able to efficiently use ABF on sagittal trunk tilt to improve their balance in the ML direction.	N/A
Gopalai et al., 2011	Integrate an intelligent vibrotactile biofeedback system with wobble board training for ankle proprioception rehabilitation and conditioning	Healthy, young individuals	IMU	1 sensor (trunk + wobble board)	Trunk angles	Minor or severe violation (A-P direction only)	Vibrotactile	The results observed an improvement in postural control with biofeedback intervention, demonstrating successfulness of the prototype	The current setup only allows for monitoring and feedback to be provided along a single plane.
Kent, Laird & Haines, 2015	(i) test the hypothesis that modifying patterns of painful lumbo-pelvic movement using motion-sensor biofeedback in people with low back pain would lead to reduced pain and activity limitation compared with guidelines-based care, and (ii) facilitate sample size calculations for a fully powered trial	Clinical (sub-acute and chronic LBP)	2 IMU's 2 EMG's	2 sensors (thoraco-lumbar junction and upper sacrum)	Self-reported pain intensity (Quadruple pain Visual Analogue Scale) and activity limitation (Roland Morris Disability Questionnaire and Patient Specific Functional Scale)	Exceeded a pre-determined angle for a sustained pre-determined period of time by the clinician	Visual and auditory/vibratory	Individualised movement retraining using motion-sensor biofeedback resulted in significant and sustained improvements in pain and activity limitation that persisted after treatment finished	Pilot trial involved co-funding and participation by the device manufacturer; Over the 12-month follow-up period the Guidelines based Care Group improved minimally; difference in the reference time period for QVAS at baseline compared with the reference period used at the follow-up time-points; the applicability of the results outside of the research context is constrained by the need for clinicians to be trained in the use of the ViMove system
Kentala et al., 2003	Evaluate the impact of a vibrotactile balance prosthesis on the performance of balance-	Clinical (Vestibular disorders)	IMU (accelerometer and gyroscope)	1 sensor (L2-L3 region)	Body tilt angle	A tilt angle range is set individually for each subject, based on his or her maximum forward and backward tilt	Vibrotactile and visual (for some trials)	Able to reduce the AP body tilt in subjects with vestibular deficits using a simple precursor to a "balance prosthesis,"; vibrotactile feedback	The prosthesis precursor is too bulky to be of use in everyday life

	impaired subjects on a moving platform					angles (on average, the maximum tilt angles were 10° forward and 8° backward)		enabled our vestibulopathic subjects to remain standing instead of falling.	
Matheve et al., 2018	(1) to assess whether sensor-based feedback is more effective to improve lumbopelvic movement control compared to feedback from a mirror or no feedback in patients with chronic low back pain and (2) to evaluate whether patients with CLBP are equally capable of improving lumbopelvic movement control compared to healthy persons	Clinical (chronic LBP)	IMU (accelerometer, gyroscope, magnetometer)	3 sensors (L1, S1, 20cm above lateral femoral condyle)	Effectiveness of feedback between baseline and post-intervention kinematics (lumbar spine and hip angles) for patients; comparing kinematics between healthy participants and patients	Continuous	Visual	Sensor-based feedback is an effective means to improve lumbopelvic movement control in patients with CLBP.	Motor learning was assessed only by transfer test, not retention; mobility of lower limb joints was not evaluated at baseline; only 3 sensors were used for measurement (only 2 for feedback)
Nanhoe-Mahabier et al., 2012	To investigate the short-term carry-over effects of one training session involving real-time vibrotactile biofeedback, as compared to a similar session of non-biofeedback training in PD patients	Clinical (Parkinson's disease)	Angular velocity sensors	2 sensors (L1 and L3) + headband for biofeedback	AP and ML displacement of the trunk (angular velocity and sway angle)	40% of the 90° ranges of pitch and roll sway angular velocity derived during the second balance assessment of the first session	Vibrotactile	One session of balance training in PD using a biofeedback system showed beneficial effects on trunk stability	First, the present intervention was brief and not very intensive; examined a small number of PD patients with a mild disease severity and without cognitive decline; patients had a relatively good balance as indicated by the high Tinetti scores, limiting the generalizability of the findings
O'Sullivan et al., 2013	To investigate how sitting behaviour is related with seated LBD, and whether using postural biofeedback which is matched to the	Clinical (Non-specific CLBP)	"Bodyguard" posture monitor with strain gauge	Spinal levels of L3 and S2	Mean lumbopelvic posture and postural variation expressed as a percentage of total lumbopelvic ROM	Individualised threshold for each subjects biofeedback was established	Vibratory	This study demonstrated that using postural biofeedback to facilitate a more neutral and less variable sitting posture significantly reduced seated LBD in a single session among people with NSCLBP	Choosing a two-point increase for categorising participants as PDs was somewhat arbitrary; LBD and OBD still increased significantly over time on both days suggesting that intermittent periods of physical activity may be needed; as PDs reported

	individual clinical presentation can reduce LBD among people with NSCLBP during a standardised seated task								significantly greater baseline disability than NPDs it suggests that greater central sensitisation among PDs contributed to the increased LBD reported during T1; No follow-up of the participants was included; participant blinding was almost impossible from nature of postural biofeedback so possibility of an enhanced placebo effect; Using a stool without a backrest does not reflect the type of seat most commonly used; Possible that discomfort may have been reduced simply due to task familiarity; Other potentially relevant parameters like muscle activation were not measured; assessor of seated discomfort was not blinded; Angular data are not provided with the posture monitor and increased forward lean can result in data exceeding the calibration value of 100% ROM
Ribeiro et al., 2020	The aim was to assess the effectiveness of a lumbopelvic postural feedback device for changing postural behaviour in a group of healthcare workers	Adult healthcare workers	Triaxial accelerometer	1 sensor (waistband)	Total number of times the postural threshold was exceeded per hour in a working week	45° lumbar spine flexion (lasting 5+ sec OR less than 25sec following first sustained posture)	Auditory	Findings indicate that audio feedback provided by a postural monitor device did not reduce the number of times healthcare workers exceeded the postural threshold.	Monitor was attached to waistband; monitor had to be replaced if monitor had significantly changed position
Sienko et. al, 2010	To investigate the effect of vibrotactile feedback during continuous multidirectional perturbations of a support platform using frequency-	Clinical (vestibular deficits)	2-axis IMU	1 sensor (lower back)	Power spectral density functions of body sway in the anterior-posterior (A/P) and medial-lateral (M/L) directions and transfer functions between platform motion and body sway	Tilt angle plus half the tilt rate exceeded a threshold of 1° (1 subject used a 0.5° threshold instead)	Vibrotactile	The reduction in gains of the frequency transfer functions computed for body sway responses in the A/P and the M/L directions suggests that the vibrotactile feedback improves the sensitivity of the	N/A

	domain techniques and stabilogram diffusion analysis							human postural control system to external platform disturbances	
Sienco et. al, 2013	To characterize the effects of two real-time feedback displays on locomotor performance during four gait-based tasks ranging in difficulty	Clinical (vestibular deficits)	IMU	1 sensor (lower back)	The root-mean-square (RMS) trunk tilt and percentage of time below the tilt thresholds	Subject-specific predefined tilt threshold; A tilt exceeding 1° (0.75° for one subject) activated the lowest factor (low level); a tilt exceeding 50% of the subject's M/L limit of stability activated all three factors (high level)	Vibrotactile	This preliminary study demonstrated that use of continuous vibrotactile feedback during challenging locomotor tasks allowed subjects with vestibular deficits to significantly decrease M/L RMS trunk tilt	Small sample size and a short training session
Stollenwerk et al., 2019	To systematically analyze geometric changes in posture as a result of postural training by a Gokhale Method teacher	Users (no info on age etc.)	Accelerometer	5 sensors (lumbar spine)	Compared snapshots of an unguided-guided posture pair based on features computed from the 2D spine curve geometry	N/a	Visual	For all three positions, sitting, standing, hip hinging, we found a significant change in posture between the sets of guided and unguided snapshot pairs	No info on participants gender, age, height or weight; number of clusters suggested by the geometry does not necessarily reflect the number of clusters found by the posture trainer; showed several samples per cluster to only one professional posture trainer for postural change evaluation
Stredova et al., 2017	Elucidate if there is a significant difference between the ability to maintain balance with or without the biofeedback while standing and identify specific segments that takes place of motion solutions of postural problems	Healthy individuals (without CNS, rheumatoid or other disease)	Triaxial accelerometer	6 sensors (2 lower leg, 2 thigh, processus spinosus vertebrae L5 and C7)	Parameter SD VPG (sum of scatter of the acceleration in measured segments in 3D which shows changes in acceleration in every directions of Cartesian system) from the VBF tasks	Continuous	Visual	Tasks with VBF shows greater SD of VPG than without VBF which shows that the conscious correction of the COP interfere to cortical system of motoric control; in eyes closed are deviations of the posture are bigger compared to open eyes. The biggest accelerations were detected in C7 in eyes closed; detected that in open eyes majority of probands used ankle strategy for maintaining balance, eyes closed preferred knee and hip strategy	Can't compare 2D and 3D data, which could cause disagreements with studies conducted in 2D
Vignais et al., 2012	Introduce an innovative and practical system	Healthy males	IMU	7 sensors (1 IMU for each upper	Percentage of time spent in pre-defined RULA score ranges (global) and	Visual (when local score was exceeded the	Visual (local scores) and	Real-time ergonomic feedback significantly decreased the outcome	Epidemiological data supporting the suggested patterns is missing; RULA

	for ergonomic assessment of a worker's activity in realtime			arm, 1 IMU for each forearm, 1 IMU for the head, placed on the STHMD, 1 IMU for the trunk, located on the chest, and 1 IMU for the pelvis, placed on the sacrum)	percentage of time spent at or above a pre-defined threshold per articulation or segment (local)	following thresholds; shoulder and upper arm: 5, elbow and lower arm: 3, wrist and hand: 5, neck and head: 4, pelvis and trunk: 4) and auditory (when global score was 7 for a period of at least 0.5 s or when global score was between 5 and 6 for a period of at least 5 s)	auditory (global score)	of both globally as well as locally hazardous RULA values that are associated with increased risk for musculoskeletal disorders.	table lacks precision; RULA table uses basic calculations which can be considered as a weakness for some specific anatomical areas like the lumbar zone; this system is not able to individually evaluate a lift and it has not yet been tested in an industrial environment; not possible to know the influence of the cumulative time spent at each range on the risk of MSDs exposure; inertial sensors and magnetometers can suffer from drawbacks such as magnetic disturbances
Volpe, Giantin, Fasano, 2014	To test the feasibility and effectiveness of a balance training program in association with a wearable proprioceptive stabilizer (Equistasi) that emits focal mechanical vibrations in patients with PD	Clinical (Parkinson's disease and history of at least one fall in the past)	"Equistasi" devices (wearable postural stabilizer)	3 sensors (over the 7th cervical vertebra and on each soleus muscle tendons)	Static posturography	N/a	Vibrotactile	A physiotherapy program for training balance in association with focal mechanical vibration exerted by a wearable proprioceptive stabilizer might be superior than rehabilitation alone in improving patients' balance	Cannot rule out the bias introduced by fluctuations in levodopa plasmatic concentration; sample size is small and results have to be replicated by larger trial; the execution of exercises were influenced by therapists' expertise and patients' motivation; WPS were only tested on the neck and soleus muscles and not in other muscles involved in posture control
Wong & Wong, 2008	Introduce a method of using tri-axial accelerometers and gyroscopes to detect postural change in terms of curvature variation of the spine on the sagittal and coronal planes and demonstrate the performance of the posture monitoring system during daily activities	Healthy individuals	Inertial (1 tri-axial accelerometer and 3 uni-axial gyroscopes per sensor)	3 sensors (upper trunk T1, mid-trunk T12 and pelvic level S1)	Tilting angles and trunk angles of the thoracic and lumbar regions, and angular velocity of trunk movements	Day 2 (sagittal plane: <math><10^\circ</math>; coronal plane: $\pm 10^\circ$); day 3 (sagittal plane: <math><5^\circ</math>; coronal plane: $\pm 5^\circ$)	Auditory	Subjects could improve their posture when feedback signals were provided	N/A
Yoon et. al, 2015	To investigate the effects of visual feedback	Healthy and clinical (CLBP)	Smart-phone (Clinometer software)	1 sensor (T10-T12)	Net angular displacement of the trunk (flexion/extension in	Continuous	Visual	VF applied through wireless smart-phone mirroring system has a	Only the static phases of trunk muscle stabilization exercises were

on internal oblique, external oblique, multifidus, and erector spinae and the kinematics of the trunk and pelvis between healthy and chronic low back pain	(Plaincode) and Mobizen software (Rsupport) were downloaded from the Google store and installed on the smart phone and computer)	sagittal plane, lateral bend in frontal plane, and axial rotation in transverse plane) and pelvis (anterior tilt/posterior tilt in sagittal plane, left pelvic drop/hike in frontal plane, and anterior/posterior axial rotation in transverse plane)	selective positive effect on trunk muscles and pelvic movement and may be beneficial for CLBP patients.	investigated; compensatory movement or subtle differences in the degree of arm and hip lift were not fully controlled; a cross-sectional method with a relatively small sample size in young subjects was used; an order effect and 2 repetitions per condition (increasing variability and random error)
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2.4. Discussion

The implementation of wearable sensory derived sensory biofeedback is becoming more broadly explored in the field of biomechanics, specifically as it relates to spine posture and motor function. Given the recent uptake of these technologies, understanding the use of this intervention to improve or alter clinically relevant outcomes is important. Given this the aim of this study was to examine the types of wearable sensor derived biofeedback currently being employed to explore and optimize spine posture and motor function biomechanics in both basic and applied research domains. It was expected that the types of biofeedback used throughout the literature would be varied; however the findings of this systematic review will synthesize data across multiple scientific domains that are using biofeedback to identify potential gaps and areas for further study.

In total 23 studies were included for full text review on the basis of the inclusion criteria for this work. Based on the quality appraisal, the studies were found to be generally of medium to high quality. Despite this there were some notable findings relating to individual items derived from the quality appraisal. First, the results of the quality appraisal suggest that the majority of studies (20/23; 16/23) provided a proper description of biofeedback (i.e., type and implementation, respectively), as well as the objectives and findings of the research (14/23; 21/23, respectively), and the full description of any statistical analyses (18/23). Second, the quality appraisal noted some consistent shortcomings across the sampled literature. In general, most studies generally failed to adequately justify sample size (16/23), properly describe movement instructions (10/23), and provide adequate detail regarding raw signal handling and processing (14/23). It is however, possible that these shortcomings are derived from the design of studies included within this systematic review. Specifically, the majority of the papers included

were written as proof-of-concept studies. With some using commercial equipment with closed-source algorithms limiting the description of any raw signal processing or handling information. Interestingly, given the novelty of wearable sensor derived biofeedback, approximately half of the studies included assessed the utility of these technology on a clinical population. In some cases the samples derived for the study were obtained through convenience sampling resulting in relatively few papers justifying sample sizes. A recent systematic review evaluating the use of wearable technology to assess spine kinematics reported that almost all studies reported research conducted in a research laboratory (Papi *et al.*, 2017). Although many of the papers included here mirror these findings, a handful of studies conducted research in the workplace, and during activities of daily living.

The data extraction procedure employed with this research uncovered several trends within the literature analyzed. First, the most common type of biofeedback employed is haptic/tactile feedback (14/23 studies). Based on the reports from studies included, haptic biofeedback tends to be easy to administer for the researcher, and easy to understand and respond to for the participants. These reports are supported by the general improvement in spine-related outcomes in the studies evaluated. These outcomes include measures such as lumbopelvic control, time spent in harmful positions, posture and balance awareness, and trunk stability. Despite this apparent prevailing bias towards haptic feedback, there still remains a lack of consensus about the most appropriate means of administering this type of biofeedback. One study administered vibrotactile feedback to the head, despite the IMU being fixed to the low back. Some studies administer multi-level vibrotactile feedback depending on various pre-determined threshold values, and some adopt a simple “on” or “off” approach. Further work is required to optimize the anatomical location, trigger/threshold, and the waveform characteristics

of any supplementary vibrotactile feedback, including a justification of these parameters to elicit an optimal motor outcome.

There are approximately equal number of studies investigating healthy participants (10/23) and clinical populations (9/23); however, only two studies compared clinical and healthy participants. This split in the research may be due to validation-type studies, given the novelty and recent uptake of wearable sensor derived biofeedback. There appears to be an agreement in the literature regarding inertial sensors as the most common sensor type used in this area of research (21/23). These findings are in agreement with recent systematic reviews performed regarding wearable sensors in spine posture analysis (*Papi et al., 2017; Simpson et al., 2019*). IMU's can be cost-effective to acquire and maintain, are easy to use and are able to produce data that are not difficult to interpret for clinicians and researchers alike. Additionally, they have been found to be reliable at measuring spine posture and movements, and can be a valuable tool to provide real-time biofeedback (*Simpson et al., 2019*).

The results presented here synthesize the literature aiming to provide wearable sensor derived sensory feedback to facilitate motor adaptations of dynamic trunk movement. The general findings of this systematic review found overall positive effects of wearable sensor derived biofeedback training on clinically relevant outcomes (i.e., spine posture, ROM and/or balance). This evidence supports the hypothesis that this technology can be used as a clinical modality to improve spine motor function and posture. Care needs to be taken in the proper reporting of any motor task, and raw signal processing. Further, future work is necessary to further optimize the use of vibrotactile feedback as a biofeedback modality to elicit motor learning. Specifically, future work is needed to optimize the anatomical location, trigger/threshold, and the waveform characteristics of any supplementary vibrotactile feedback.

Collectively the research papers evaluated here suggest strong promise in the use of biofeedback to compliment the current uptake of wearable sensors in spine posture and movement retraining.

2.5. Bridge Summary

As noted previously, Study #1 revealed positive effects of wearable sensor derived biofeedback on spine motor control. Despite the benefits noted previously, gaps still exist regarding the potential benefits of wearable sensor derived biofeedback on lumbar spine proprioception. The findings of the Study #1 revealed a prevailing bias towards vibrotactile biofeedback in the literature, however, it is known that certain afferent channels may be affected in lower back disorders. Thus, it is possible that unaffected afferent (i.e., auditory) channels may be particularly useful in a sensorimotor (re)training context to improve lumbar proprioception and to avoid future injury. This work will provide the framework to further understanding the potential use for wearable sensor derived biofeedback in a clinical setting.

CHAPTER III – STUDY #2: ASSESSMENT OF THE ACUTE EFFECTS OF WEARABLE SENSOR DERIVED AUDITORY BIOFEEDBACK ON GROSS LUMBAR PROPRIOCEPTION

3.1 Introduction

Low back pain (LBP) continues to be the leading cause of activity limitation and is the most common musculoskeletal disorder globally (Hurwitz *et al.*, 2018; Wu *et al.*, 2020). The neuromuscular control of the spine leverages sensory feedback from multiple afferent inputs, incorporating sensory feedback to create a certain muscular response. Integration of natural proprioceptive inputs with supplementary sensory inputs, such as supplementary auditory feedback has become very common with the recent advent of wearable sensors and devices (Sigrist *et al.*, 2013; Alhasan *et al.*, 2017; Beaudette *et al.*, 2018). Specifically, augmented and supplementary biofeedback can be used as a training method that provides additional information to enhance performance through changed behaviours (Alhasan *et al.*, 2017). For example, auditory biofeedback has been used previously in biomechanical feedback for numerous body regions (e.g., knee, ankle, trunk, hand), and demonstrated promising results when implemented in a gait and postural control sensorimotor re-training context (Giggins *et al.*, 2013).

In most cases, clinical assessments rely heavily on subjective reporting to quantify motor impairments. Unfortunately, such assessments suffer from poor reliability, suggesting the need for more objective scoring metrics (Cook *et al.*, 2006). Due to the large cost and space requirements of conventional laboratory motion capture equipment, there has been a disconnect between objective measures collected from laboratory settings and the utility of these measures in clinical settings. Wearable sensors can capture biomechanical data and generate meaningful sensory biofeedback based on these acquired data at a fraction of the cost, and with no

specialized space requirements. Therefore, wearable sensors are a valuable solution for bridging the current gap between the research lab and clinic as they are an affordable and practical way to incorporate objective data regarding motor control into a clinical setting (Papi *et al.*, 2017).

Given the recent uptake of wearable sensors in both laboratory and clinical settings, it is important to understand how wearable sensors can be used in a sensorimotor (re)training approach, including how sensor-derived biofeedback can be used to improve measures of gross spine motor control and proprioception.

Proprioception is one's intrinsic ability to perceive joint and body movements, senses of effort, force, and heaviness, as well as the body's position in space (Han *et al.*, 2016; Proske & Gandevia, 2012). Proprioception can be impaired on a mechanical level (e.g., damage of tissues, muscle fatigue) or without any change at the level of the peripheral sensor (e.g., central sensitization, cortical re-organization), with the latter being linked with patients who suffer from chronic pain (He & Kim, 2021; Zhang *et al.*, 2019). Proprioception has been quantified and measured in many ways, typically depending on whether researchers intend to target active or passive subsystems. Further, proprioceptive control can be assessed under conscious or subconscious conditions. For example, conscious proprioceptive control can be measured through completion of a re-matching task and quantifying joint repositioning error. An example of an assessment of subconscious proprioceptive control would be the assessment of a natural response to muscle vibrations (e.g., on postural sway characteristics). Previous research suggests that individuals who suffer from LBP have impaired proprioception of the trunk, specifically a decreased ability to detect changes in trunk position and significantly higher repositioning error during a flexion repositioning task when compared to healthy individuals (Lee *et al.*, 2010; Newcomer *et al.*, 2000). Additionally, Claeys *et al.* (2010) reported that patients with non-

specific LBP demonstrate a less optimal postural control strategy, indicating a decreased proprioceptive reweighting capacity.

The purpose of this study was to explore the potential acute benefit of wearable sensor-derived auditory biofeedback on the conscious proprioception of the lumbar spine. Specifically, assessing the differences in proprioception across four different flexion targets, assessing the effects of acute auditory biofeedback and identifying if potential benefits of auditory biofeedback are modulated by baseline proprioceptive abilities. It was hypothesized that auditory biofeedback training will be effective at acutely improving accuracy and precision of lumbar spine sagittal plane repositioning across all four of the targets, an indicator of an improved conscious proprioception of the lumbar spine.

3.2 Materials and Methods

3.2.1 Participants

28 healthy, young adults participated in this study (Table 5). The sample size was chosen based on previous research (Ruggerio *et al.*, 2016; Hidalgo *et al.*, 2013), and to facilitate the study design. Participants were eligible if they were between 18 and 30 years of age. Exclusion criteria included any recent (i.e., within the last three months) history of low back pain, neurological, orthopedic, auditory, or muscular disorders or current upper respiratory infection that may affect their balance or hearing. Further, all participants were free of any known allergies to rubbing alcohol or adhesives. All participants completed a general health history questionnaire and provided electronic informed consent prior to the data collection. The protocol has approval of the local research ethics board, in accordance with the Declaration of Helsinki.

Table 5. Participant demographics.

	Mean (standard deviation)
Females (n)	14
Males (n)	14
Age (years)	22.9 (3.4)
Weight (kg)	73.4 (13.9)
Height (cm)	172.8 (9.5)

3.2.2 Participant Instrumentation

Participants were instrumented with two, body worn, experimental sensors. A wireless 2D electrogoniometer (Biometrics Ltd., SG150) was used to track the flexion-extension angle of the lumbar spine at T12 and S1 levels (Figure 3). The electrogoniometer was attached to one wireless IMU sensor (Noraxon Ultium) which is attached over the iliac crest using double-sided adhesive. The additional sensor transmits all relative spine flexion-extension and lateral bending angles to a wireless receiver. All equipment was placed with the participant in a comfortable seated position.

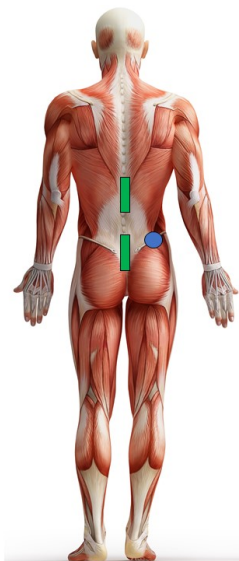


Figure 3. Experimental and participant set up including electrogoniometer (green rectangle) and wireless sensor (blue dot) locations in the posterior view.

3.2.3 Protocol

Each participant was required to attend the laboratory for one two-hour data collection. Participants were asked to refrain from strenuous exercise for 48 hours prior to their testing session to prevent delayed onset muscle soreness which may have the capacity to interfere with conscious proprioception (Houle *et al.*, 2020). The first 30 minutes consisted of participant instrumentation, range-of-motion (ROM) assessment, and familiarization with the task. In the remaining 1.5 hours, the repositioning tests and auditory feedback training were completed. Both tasks were completed with participants sitting in an ergonomic kneeling chair to ensure that the movement of the pelvis is naturally restricted (Figure 5) (i.e., Ruggiero *et al.*, 2016). Flexion ROM of the lumbar spine was assessed by asking the participant to flex and extend their spine as much as they can in a slow and controlled manner three times. Once complete, the target values for the repositioning tasks (20%, 40%, 60% and 80% of ROM) were derived from the flexion ROM assessment directly after completion to ensure that all repositioning targets were relative to the participant size and flexibility. A maximum of two familiarization repetitions per target were completed, for a total of eight potential repetitions to familiarize participants with the target angles and the repositioning task, as well as to wash out any acute learning effects from the pre and post analyses.

The structure of the remaining portion of the protocol was as follows: (1) pre-training repositioning tests (20, 40, 60, and 80% ROM), (2) training with the auditory biofeedback for two counterbalanced targets, (3) post-training repositioning tests (20, 40, 60, and 80% ROM) (Figure 4). The order of target presentation, and the selection of training targets, were presented to participants following a randomized complete block design (RCBD). During the pre-training test, participants were required to perform a trunk flexion repositioning task five times at each of

the four targets, completed in a random order, for a total of 20 repositioning repetitions in the pre-training test. For each repetition of the repositioning task, the participant started in a self-selected neutral seated posture with their eyes closed, with an angle between the thigh and trunk of approximately 130°. The participant was instructed to flex their lumbar spine to the appropriate target angle and received verbal feedback from the researcher present when they have reached the target angle. The participant was instructed to maintain that position for approximately two seconds, before returning to their self-selected neutral position. The participant was then asked to return to the target angle without any feedback from the researcher. Following the completion of all 20 repetitions, participants were able to take a three-minute break before the training sessions to avoid any effects related to acute muscle fatigue.

The training sessions consisted of two target angles, one above and below 50% maximum ROM, chosen and completed according to the study design (RCBD). The participant received auditory feedback derived from a wireless electrogoniometer sensor for a minimum of five minutes, and a maximum of six minutes per target, with a one-minute break between targets. The order of the targets during this training period was randomized. The auditory biofeedback was administered in an instantaneous, “online” manner. When participants entered the target range, they would hear a continuous, steady tone. When they exited the target bounds they would hear a single, short directional tone (i.e., “higher” tone for extension, “lower” tone for flexion). Participants were instructed to move freely throughout their ROM with their eyes closed, with the goal of trying to find the target, understanding what it feels like to be at the target and trying to memorize/internalize the target using the auditory feedback. Following the completion of the training session, participants were allowed to take a three-minute break (maximum) before the post-training test. The duration of this break was capped to ensure that the training is retained,

and the assessment of the training could proceed in a timely manner. The post-training test mirrored the methods outlined in the pre-training test, such that the randomised order of targets in the pre-test was retained for the post-test.

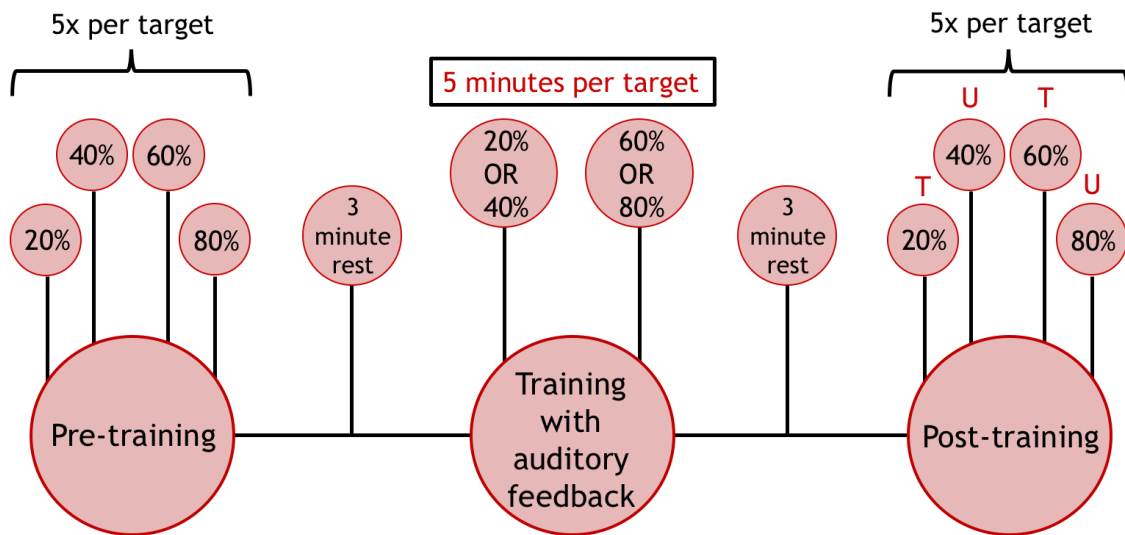


Figure 4. Visual representation of the study protocol following the familiarization trials. “T” and “U” denote trained and untrained targets, respectively, as an example.

3.2.4. Data Processing

Wireless flexion-extension angles obtained from the electrogoniometer were smoothed using a recursive digital 4th order low-pass Butterworth filter with a cut-off of 6 Hz. Once filtered, raw time series data were visually inspected to identify the onsets and offsets of each targeting task (i.e., both the assignment of the original target and the participant’s attempt to re-match the target) (Figure 5). Once identified, the mean flexion angle was computed using these events to represent each target, and these means were used to approximate the following outcomes: (1) Constant error (CE) – which represents the average error across all five repeated trials for each target with positive values indicating an overshoot during rematching and a

negative value indicating an undershoot during rematching, (2) Absolute Error (AE) – which represents the absolute value of the constant error and treats overshooting and undershooting equally, and (3) Variable Error (VE) – which is calculated as the standard deviation of all CE values over the five repetitions for each target (Beaudette, 2018). CE values were interpreted to quantify any persistent over or undershooting. AE values were interpreted to quantify the absolute magnitude of error, a measure of accuracy. VE values were interpreted as the variability in the error, a measure of precision. As noted previously, CE, AE and VE values were expected to improve (i.e., tend towards zero) with acute wearable sensor mediated auditory biofeedback, indicative of improvements in lumbar proprioception. To facilitate statistical comparison across all parameters, mean CE and AE values were taken across all five target repetitions. Further, POST-PRE differences (i.e., delta-CE, delta-AE, delta-VE) were taken for all three parameters to quantify any changes for each parameter across both timepoints.

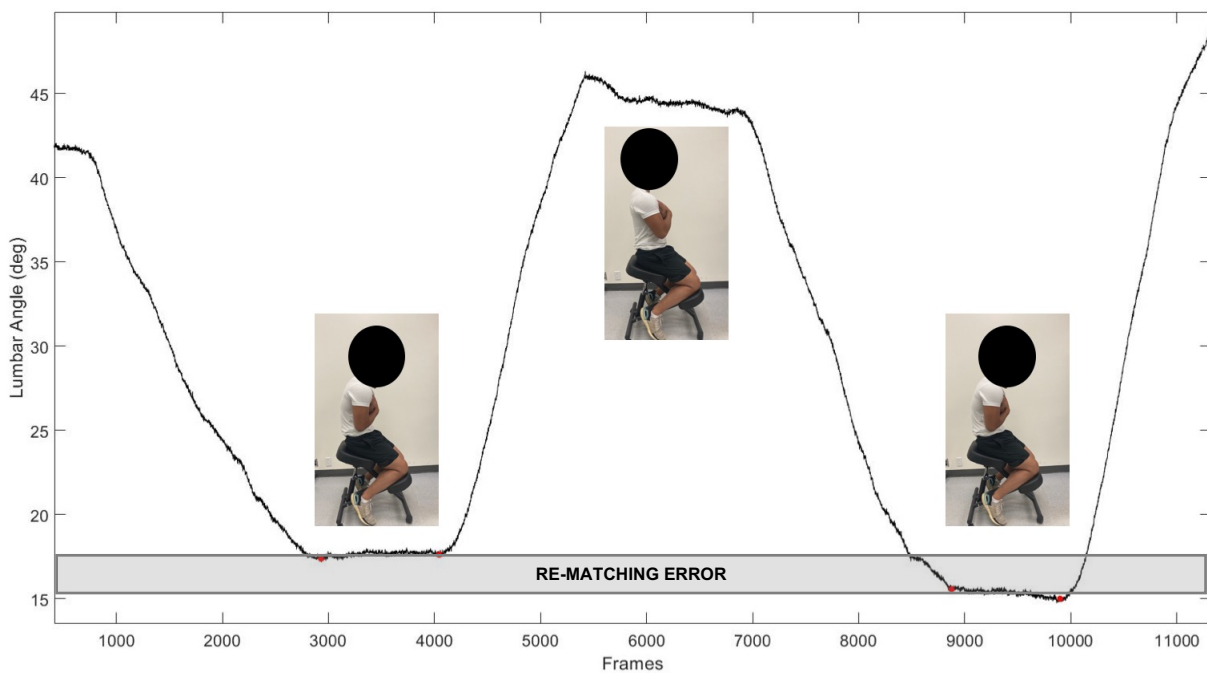


Figure 5. Representative data depicting repositioning task and error for a single participant.

3.2.5. Statistical Analysis

Statistical analysis was conducted using SAS (v9.4, SAS Institute Inc.). A two-way ANOVA was conducted to assess the differences between trained and untrained targets (i.e., the effects of auditory feedback), as well as differences between each of the targets on dependent variables which included delta-CE, delta-AE, and delta-VE. Assumptions of normality were tested using a Shapiro-Wilk test statistic. Following the interpretation of any statistically significant main effects a Tukey post-hoc analysis was performed to facilitate multiple means comparison. To identify if any potential benefits of auditory feedback are modulated by baseline proprioceptive ability, a linear regression analysis was performed to assess the level at which the amount of change seen between pre- and post-training can be explained by the pre-training error. A correlation co-efficient was calculated to compare the difference between pre-training averages and delta-AE, delta-VE, and delta-CE to examine the relationship between the pre-training re-matching abilities and the capacity for change. Correlation coefficients are interpreted on a scale from -1 to +1, with -1 and +1 being strongest correlation, and 0 representing no correlation. The significance level for all analyses was set to $p < 0.05$. If required, outliers were removed when studentized residuals exceeded a value of ± 3 . Unless otherwise stated, all data are presented as means \pm standard errors.

3.3 Results

Following the removal of outlying data points ($n = 3$), a Shapiro-Wilk test suggested parametric analyses were appropriate for the study data ($W = 0.9835$, $p = 0.2014$). In the assessment of delta-CE, the repeated measures ANOVA did not reveal any significant main target ($F = 0.76$, $p = 0.5170$), training ($F = 0.20$, $p = 0.6573$), or target*training ($F = 0.40$, $p = 0.7530$) effects. In the assessment of delta-AE, the repeated measures ANOVA did not reveal

any significant main target ($F = 0.38$, $p = 0.7654$) or training ($F = 1.39$, $p = 0.2409$) effects; however, a significant target*training interaction ($F = 2.71$, $p = 0.0488$) was observed. Despite this, post-hoc analyses did not reveal any significant comparisons (Figure 6a). In the assessment of delta-VE, the repeated measures ANOVA did not reveal any significant main target ($F = 0.70$, $p = 0.5568$), training ($F = 3.44$, $p = 0.0666$), or target*training ($F = 1.25$, $p = 0.2947$) effects (Figure 6b).

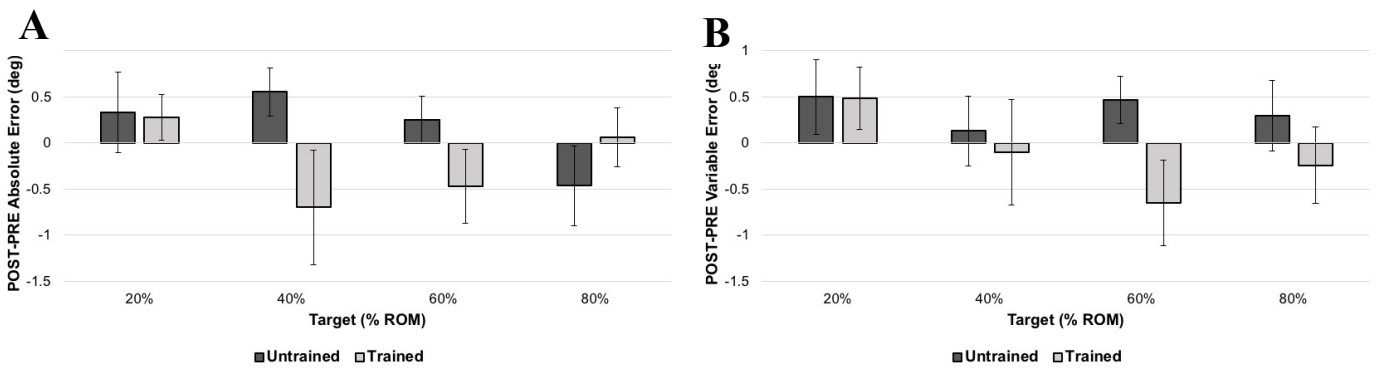


Figure 6. Comparison of delta-AE (A) and delta-VE (B) between each of the four targets in both trained and untrained conditions.

Complementing these results, the correlation analyses revealed a moderate-strong negative correlations for all error metrics (i.e., CE, AE, and VE) at the 60% target, VE at 40% (moderate) and CE and AE at 40% (strong). Additionally, a strong negative correlation at the 80% target for AE and VE. Interestingly, there was a weak negative correlation at the 20% target (Table 6; Figure 7).

Table 6. Correlation coefficients for each target based on pre-training values and delta-error values. Values between < -0.6 indicate a weak correlation, -0.6 indicates a moderate correlation and -0.8 indicates a strong correlation.

Target (% ROM)	Correlation Coefficients (R values)		
	CE	AE	VE
20	-0.544	-0.511	-0.573
40	-0.827	-0.843	-0.622

60	-0.662	-0.739	-0.745
80	-0.518	-0.706	-0.815

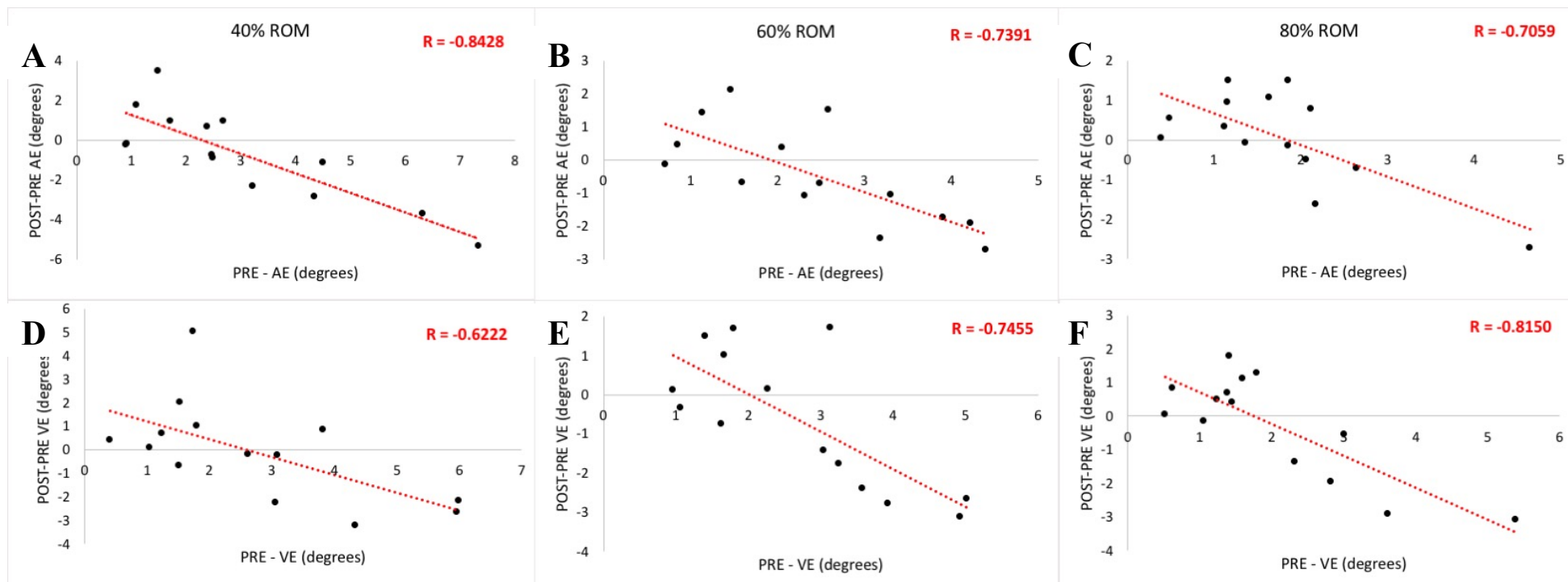


Figure 7. Linear regressions for the 40%, 60% and 80% ROM targets for AE (A-C) and VE (D-F) depicting the relationship between pre-training proprioceptive abilities (x-axis) and amount of change from pre- to post-training (y-axis).

3.4 Discussion

The goals of this study were threefold: (1) to assess differences in proprioception across four different trunk flexion-extension targets, (2) to assess the effects of acute auditory biofeedback, and (3) to identify if potential benefits of auditory biofeedback are modulated by baseline proprioceptive abilities. The main finding of this study is that young, healthy individuals stood to benefit from acute auditory biofeedback training at three of the four targets, which was moderately dependent on their baseline trunk proprioception.

There was a positive effect of acute auditory biofeedback training, specifically for AE; however, when looking across the entire sample of participants the effects were small. As noted by the significant main effect ($F = 2.71$, $p = 0.0488$) of target by training, there is evidence that those who were trained with biofeedback demonstrated an average improvement in their accuracy of re-matching some of the targets. Although post-hoc analyses were insignificant, Figure 6a suggests that targets 40% ROM and 60% ROM benefitted the most from acute auditory biofeedback training. One possible reason that participants showed negligible improvements at the 20% ROM target is that there was insufficient mechanical change to the system to provide meaningful mechanical stimulation to the mechanoreceptors responsible for proprioception. Specifically, a lack of change at the sensors such as the muscle receptors (e.g., muscle spindles, Golgi tendon organs) or skin receptors (e.g., Ruffini endings) which would respond to muscle length/tension and skin stretch. Another potential factor to consider when comparing postural targets is the presence of the flexion-relaxation phenomenon (particularly at targets exceeding 70% flexion range-of-motion). Specifically, the flexion-relaxation phenomenon occurs when there is an electrical silence observed in the erector spinae muscle group at full or near-to-full trunk flexion (Kippers & Parker, 1984; Schinkel-Ivy *et al.*, 2014).

This phenomenon is observed in healthy individuals, and can be impaired (i.e., absent) in people with chronic or acute low back pain, such that there is no relaxation of the erector spinae at end range (Mak *et al.*, 2010). With the 80% ROM target presented here, there is potential for a reduced role of muscle-derived proprioceptive afferent information, thereby generating a preferential reliance on proprioceptive afferents embedded in deeper (i.e., passive) ligamentous structures, or those located superficially (i.e., in the skin). Based on the linear regression analyses presented here (Table 6; Figure 7), the 80% ROM target improved in both AE and VE in individuals who had poorer proprioception at baseline. Assessing targets that span the trunk flexion-extension ROM has been done before (Newcomer, 2000; Lin *et al.*, 2006, Descarreaux *et al.*, 2005); however, most studies have observed differences in repositioning errors at a single target between healthy and a clinical population and have not assessed the potential benefits in implementing biofeedback at multiple postural targets.

Despite the significant main effects reported above, the results of the study suggest that the acute effects of auditory biofeedback training are negligible when interpreting mean group effects. Nevertheless, within the dataset presented there were a range of recorded responses to the acute biofeedback intervention. Therefore, to understand if those with poorer proprioceptive abilities stood to benefit from acute biofeedback training (i.e., mirroring potential proprioceptive deficits observed in clinical groups), a regression analysis was performed. Through this analysis there are some differences in the benefit of acute auditory biofeedback training across different flexion-extension targets. Specifically, the smallest target (20% ROM) showed a weak correlation between pre-training abilities and amount of change/improvement derived from the acute biofeedback intervention. Despite this, all of the other targets exhibited moderate-strong and strong negative correlations, particularly when assessing AE and VE. This suggests that

those with the poorest abilities at baseline stood to benefit the most from the auditory sensory feedback paradigm employed here. As noted previously, potential differences in proprioceptive abilities at different targets are of particular interest given the role of proprioceptive sensors in providing afferent feedback at these targets.

There is the potential for these findings to be integrated into a clinical setting to work to optimize the implementation of biofeedback. This could be a result of utilizing proprioceptive assessment and training as part of the clinical decision-making process (Figure 8). As it is currently unclear whether proprioceptive deficits precede the development of LBP or vice versa, it is important to treat this approach with a continuous re-assessment loop.

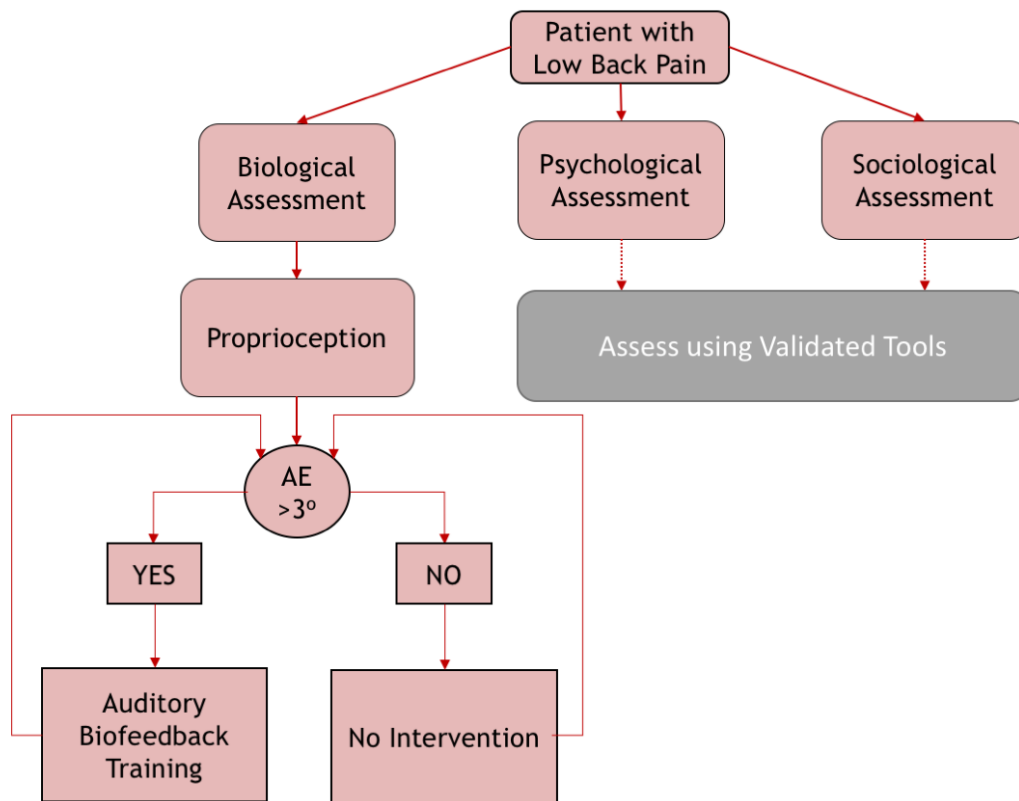


Figure 8. An example of the clinical decision-making process incorporating proprioceptive assessment.

Collectively, the results of this study demonstrate that benefits of auditory biofeedback are affected by baseline proprioceptive abilities. In general, participants who began with greater proprioceptive abilities (i.e., lower error values) had a smaller window for improvement and participants who began with greater error values generally had a greater margin for improvement. The ceiling effect noted may be one explanation for statistically insignificant group-level findings reported here. Although some research is inconclusive (Lee et al., 2010; Descarreaux et al., 2005), Wilder *et al.* (2011) reported that healthy individuals had a repositioning error between one and two degrees, and those with LBP had repositioning errors of approximately two times that. This study had AE and VE ranging from less than one degree to almost five degrees. To conceptualize these results, these values can also be normalized and expressed as a percentage of the individual's ROM. In this study, those error values translated to 1% of flexion ROM for some, while others had error values upwards of 20% of their flexion ROM suggesting that small changes or improvements in one's proprioceptive ability (particularly for those with poor baseline proprioceptive abilities) may be more advantageous for some individuals than others.

3.4.1. Limitations

There are limitations that should be considered in interpretation of this study. First, the training for each participant was not standardized beyond having them remain seated and with their eyes closed. Participants may have focused on structures, sensory cues, or anatomical areas other than the lumbar region to train their repositioning movement. Given this, some participants may have adopted more effective training principles than others, and therefore stood to benefit from the auditory biofeedback training more. Second, given the sample used here, there is a clear ceiling effect present within the dataset affecting the interpretation of any group-based analyses.

This current study assesses the proprioception of healthy, young adults, all of whom should not be experiencing proprioceptive deficits at the time of testing. Nevertheless, the regression analysis utilized here suggests that those with poorer proprioceptive abilities stand to benefit from acute sensor-derived biofeedback training. Therefore, this proprioceptive re-training technique may be of use in a clinical (i.e., LBP) population where group-level proprioceptive deficits are apparent. The presentation of the repositioning task in this protocol is inherently noisy, as certain task parameters are not constrained (i.e., speed of repositioning movement). Given that muscle spindles are sensitive to changes in velocities, this presents as a methodological limitation. However, participants were encouraged throughout the protocol to move slowly, and tended towards a slower pace as the targets were presented randomly. Finally, the five minute training period using the auditory feedback has not been previously assessed as a standardized length of time for training. As such, there is potential for participants to experience localized fatigue of the trunk as a result of the protocol. There was no quality assurance that the effects of fatigue could not have set in aside from verbal communication between the researcher and the participant. The effects of fatigue can alter an individual's movement patterns, and therefore could limit the comparability between pre- and post-testing measures. However, this limitation is mitigated through the use of timed breaks throughout the protocol, and the low physical demand of the repositioning and training tasks.

3.5 Conclusions

This study demonstrated the ability for wearable sensor-derived auditory biofeedback to improve lumbar spine proprioception in a healthy, young population; particularly in those who had poorer proprioception to begin with. Given the knowledge that low back proprioception is

impaired in individuals who suffer from LBP, it is important to consider potential methods for improving their proprioception as a part of rehabilitation. Auditory biofeedback is simple to understand and can be provided both with and without supervision by a healthcare professional. This is a particularly relevant finding given that wearable sensors continue to become more accessible and affordable and can be easy to use in a clinical rehabilitation setting.

CHAPTER IV – SUMMARY, CONCLUSIONS AND FUTURE DIRECTIONS

Previous work has demonstrated the link between LBP and impaired proprioception of the trunk (Lee *et al.*, 2010; Newcomer *et al.*, 2000). Given the recent uptake of wearable sensors, there is a place to investigate the utility of various modes of biofeedback derived from these technologies. The broad goal of this thesis was to gain a better understanding of the utility of wearable sensor derived biofeedback on the motor control of the lumbar spine. This goal was addressed through two complimentary studies.

Study #1 aimed to synthesize and explore the types of wearable sensor derived sensory biofeedback currently being employed to explore and optimize spine posture and motor function biomechanics in various research domains. Most papers were rated medium quality, and were generally good at reporting details relating to biofeedback; however, were lacking in details regarding study design and sample population. This systematic review revealed that most studies tend to employ real-time biofeedback, typically instantaneous, though it depends on the type. Further, vibrotactile feedback was identified as the most commonly used sensory stimulus throughout the research literature. Collectively, this body of literature would benefit from coming to a consensus regarding the most effective means of delivering common types of biofeedback (i.e., vibrotactile).

Study #2 investigated the utility of auditory feedback derived from a wireless electrogoniometer as a training tool to improve gross lumbar spine proprioception. Previous literature suggests that individuals suffering from LBP have impaired proprioception of the trunk (Lee *et al.*, 2010; Newcomer *et al.*, 2000), and auditory biofeedback has demonstrated promising results when implemented in gait, or numerous other body regions (Giggins *et al.*, 2013). Active repositioning of the lumbar spine improved most at the mid-range (40% and 60% ROM) targets,

with the 20% and 80% ROM targets demonstrating negligible differences when compared to the untrained targets. Despite the absence of significant group-level effects, linear regression analyses suggest that baseline proprioceptive abilities are relevant, as those with poorer baseline proprioception benefitted most from the auditory biofeedback training intervention. These findings suggest that auditory biofeedback may be useful as a sensorimotor retraining tool, specifically in a clinical population, or in those who present with proprioceptive deficits of the trunk.

Collectively, the findings of this thesis lay the groundwork for further research into sensory biofeedback as a training tool. Although a substantial amount of research has been done surrounding vibrotactile feedback, future research is required to optimize the implementation of this feedback in a clinical setting. Further, acute auditory biofeedback training appears to have merit as a means to improve proprioceptive abilities in those with apparent proprioceptive deficits. Given this, further assessment of auditory biofeedback training is warranted by potentially evaluating a clinical population, and the retention of training benefits.

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APPENDIX I – CONSENT FORM

Date: June 2021

Project Title: The acute effects of proprioceptive training of the low back using wearable sensor derived auditory biofeedback

Principal Investigator:

Dr. Shawn Beaudette
Assistant Professor
Brock University
Ph: 905-688-5550 x6687
E: sbeaudette@brocku.ca

Principal Student Investigator:

Ms. Aurora Battis
Graduate Student
Brock University
Ph: 905-688-5550 x5623
E: ab15rd@brocku.ca

INVITATION

You are invited to participate in a research study assessing individual responses to the use of auditory biofeedback to improve low back proprioception. During this study we will be quantifying your ability to re-match spine flexion targets before and after auditory feedback training. The purpose of this study is to examine whether auditory biofeedback training can acutely improve lumbar spine proprioception. If you have any questions or concerns about the research, please contact the researchers. The research is a single-site project. There are no conflicts of interest on the part of the researchers or their institution. This research is funded by the Natural Sciences and Engineering Council (NSERC) of Canada (RGPIN-2020-05195).

To be eligible for this study, you must:

- be between 18 (17 if a Brock student) and 30 years old
- be in good general health
- have not experienced low back pain within the past 3 months
- be free of any neurological (e.g., concussion within the past six months, Parkinson's disease, Amyotrophic Lateral Sclerosis, Multiple Sclerosis, vertigo, etc.), orthopedic (e.g., recent fracture, osteoporosis, osteoarthritis, etc.), muscular (e.g., recent sprain, strain, or tendonitis, muscular dystrophy, etc.), or hearing injuries or disorders and current upper respiratory infection that may interfere with your balance, mobility or hearing
- not have any known allergies to rubbing alcohol or adhesives

**Do you think you are eligible for this study? _____ (Please indicate YES or NO)
(If you are unsure of your eligibility, please contact the researchers for any clarification)**

WHAT'S INVOLVED

As a participant, you will be asked to perform the following tasks during one single 2-hour testing session at the Spine Biomechanics and Neuromuscular Control Laboratory (WH23) at Brock University. Throughout the experiment, you will be required to wear comfortable athletic shorts or pants, and athletic shoes.

Experimental Set-up (approximate duration: 10 minutes):

During this stage of the experiment you will be asked to sit while the experimental sensors are placed on your skin. For this experiment, two types of experimental sensors will be placed at specific locations on your body. An electrogoniometer will be placed on your skin using adhesive tape and two fabric belts to track the angle of your lumbar spine. Additionally, a wireless sensor will be placed on your skin using adhesive tape to facilitate transmission of data derived from the electrogoniometer to the computer. The locations of the electrogoniometer and wireless sensor can be seen in the picture below.

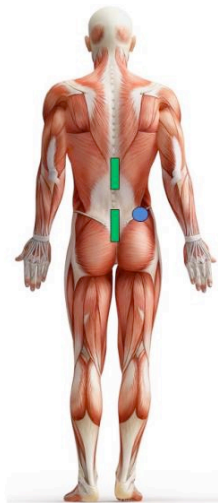


Figure 1. Experimental and participant set up including electrogoniometer (green rectangle) and wireless sensor (blue dot) locations in the posterior view.

Range of Motion Assessment (approximate duration: 10 minutes): With all the equipment in place, a procedure will take place to measure your functional trunk range-of-motion (ROM). To measure this, you will be asked to move your trunk as far as you are comfortable in a forward direction while seated in an ergonomic kneeling chair. An image demonstrating the ROM assessment can be seen below.

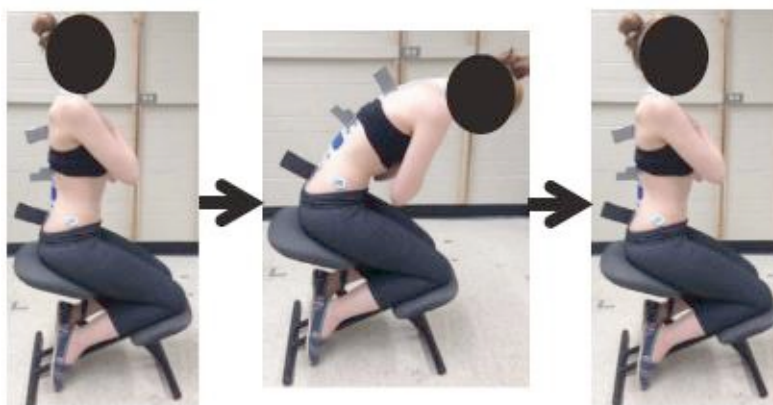


Figure 2. Demonstration of the functional ROM assessment during spine flexion-extension. *Note: female participants will be allowed to wear a shirt during this study protocol.*

Familiarization (approximate duration: 10 minutes): You will complete two familiarization repetitions for each of the four targets in a random order. The familiarization trials will be completed with the same steps during pre- and post-training tests (outlined below).

Repositioning Tests and Auditory Feedback Training (approximate duration: 90 minutes): The structure of this will be a pre-training test, a training session, followed by a post-training test. You will be required to sit in the ergonomic kneeling chair, beginning in a neutral posture. For each repositioning repetition, you will have your eyes closed and be instructed to move your trunk forward slowly until the researcher indicates that you have reached the target angle. You will be asked to hold that position for about two seconds, and then continue moving your trunk forward as far as you are comfortable. From here, you will be asked to return to the target position without any feedback from the researcher. This will be completed for all four targets five times, for a total of 20 repetitions in the pre-training test. Two of the four target angles will be trained using auditory biofeedback for at least five minutes each. During this time, you will be asked to move freely throughout your ROM with your eyes closed trying to memorize the target. You will be allowed to take a three-minute break between training sessions. The post-training test will follow the same steps as the pre-training test.

POTENTIAL BENEFITS AND RISKS

The data collected from the study has no direct benefit to you as a participant. However, you will have the opportunity to learn more about biomechanics and motor control research through your involvement in the experiment. More broadly, the results from this study will help contribute to our understanding of the acute effects that auditory biofeedback facilitated by wearable sensors as a training tool has on the proprioception of the lumbar spine.

There are risks associated with participation. First, there is a mild risk of delayed onset muscle soreness following the study protocol, due to repeated flexing of the trunk. This risk will be managed by giving you short breaks as needed between trials. Second, there exists a small risk of experiencing irritation/itching from placement of the sensors on the skin. This risk will be managed through use of hypoallergenic materials as much as possible. Please alert the investigator if you feel any pain or discomfort during or after the experiment. You will be informed in advance of any materials that will contact your skin. Third, it is possible that you may feel self-conscious while participating in this study while your back is exposed. To accommodate this, all experiments will be completed behind closed doors. Further, if desired, you can request to have a researcher of the same-sex apply the required equipment (i.e. electrogoniometer and wireless sensor). In addition, no photographic data will be collected throughout this study, and you will be free to wear any athletic clothing you bring to the experimental session.

CONFIDENTIALITY

All information that you provide is considered confidential. Your name will not be included or, in any other way, associated with the data presented in study reports. You will be assigned a code number so that your name cannot be connected to the data collected. Furthermore, because our interest is in the average responses of the entire group of participants, you will not be identified individually in any way in written reports of this research. Data collected during this study will be stored in a locked cabinet and on password-protected computers in the Spine Biomechanics and Neuromuscular Control Laboratory at Brock University (WH 23). Only the

investigators of this study will have access to the data. With your additional consent (below) data will be maintained indefinitely in a study database to support future secondary uses. Otherwise, data will be kept for five years following the publication of the study, after which time the data will be destroyed.

SECONDARY DATA USES

The investigators are interested in potential secondary uses for the study data. Through these secondary uses, current and future trainees studying within the Spine Biomechanics and Neuromuscular Control Laboratory will have access to use your study data for other projects and purposes outside of this current project, but within the area of biomechanics and neuromuscular control. If you elect to allow for secondary uses of the study data (second signature line at the end of this form) your study data will be maintained indefinitely under a participant specific numerical identifying code. Identifying information (i.e., your name) will also be maintained indefinitely within a single electronic form accessible by only the principal investigator. This form will be used to link your name to a specific numerical participant identifier, which will be used to file the remainder of the data gathered through this study.

VOLUNTARY PARTICIPATION

Participation in this study is voluntary. You may choose not to perform any or all of the trials included in the study. You may also withdraw from this study at any time during the experiment and without penalty by informing the researchers of this study. Your participation, non-participation or your withdrawal will not affect your current or future standing at Brock University. If you withdraw from the study, you will have the option for your computerized data records to be deleted, and physical records to be destroyed.

PUBLICATION OF RESULTS

Results of this study may be published in professional journals and presented at conferences. General feedback (i.e., research findings) about this study will be available at the conclusion of the research project. Should you wish to receive a summary about the study results, please complete the attached "Request for Summary of Results" form. Please note that individual feedback will not be available because results are analyzed as part of a larger data set.

CONTACT INFORMATION AND ETHICS CLEARANCE

If you have any questions about this study or require further information, please contact the Principal Investigator using the contact information provided on the first page. This study has been reviewed and received ethics clearance through the Research Ethics Board at Brock University (20-366). If you have any comments or concerns about your rights as a research participant, please contact the Office of Research Ethics at (905) 688-5550 Ext. 3035, reb@brocku.ca.

Thank you for your assistance in this project. Please keep a copy of this form for your records.

INFORMED CONSENT

I agree to participate in the study described above. I have made this decision based on the information I have read in the Informed-Consent Letter. I have had the opportunity to receive

any additional details I wanted about the study and understand that I may ask questions in the future. I understand that I may withdraw with this consent at any time.

Name: _____ (please print)
Signature: _____ Date: _____

SECONDARY DATA USES

I agree to allow for any secondary uses of my study data. This includes the indefinite retention of the data gathered through this study, and the maintenance of a digital form linking my name to my numerical participant identifier (only accessible by the Principal Investigator). I have made this decision based on the information I have read in the Informed-Consent Letter. I have had the opportunity to receive any additional details I wanted about secondary data uses and understand that I may ask questions in the future. I understand that I may withdraw with this consent at any time.

Name: _____ (please print)
Signature: _____ Date: _____

**Department of Kinesiology, Brock University
Request for Summary of Results**

June 2021

Title of Study: The acute effects of proprioceptive training of the low back using wearable sensor derived auditory biofeedback

Principal Investigator:

Dr. Shawn Beaudette, Assistant Professor, Department of Kinesiology, Brock University

Principal Student Investigators:

Ms. Aurora Battis, Graduate (MSc) Student, Kinesiology, Brock University

If you would like to receive a copy of a summary of the results of this study by email, please complete the following information:

Name: _____

Email: _____

If you would like to receive a copy of a summary of the results of this study by mail, please complete the following information:

Name: _____

Address: _____

City: _____

Postal Code: _____

APPENDIX II – HEALTH HISTORY QUESTIONNAIRE

General Health History Form

Age:

Sex:

Height:

Weight:

1. Have you ever experienced pain in the low back region that has caused you to miss school, work or any regular activity?

Yes (If Yes, please describe)

No

Date:

2. Have you ever sought medical treatment (physician, chiropractor, physiotherapist) relating to your low back region?

Yes (If Yes, please describe)

No

Date:

3. Have you ever experienced skin sensitivity or an allergic reaction to adhesives such as medical tape or medical electrodes?

Yes (If Yes, please describe)

No

4. Have you ever sought medical treatment relating to a skin condition in the region of the low back?

Yes (If Yes, please describe)

No

Date:

5. Do you regularly engage in any type of physical activity?

Yes (If Yes, please describe)

No

6. Have you ever been classified as having a musculoskeletal (e.g. Parkinson's Disease or Cerebral Palsy) or Neurological (e.g. Diabetic Neuropathy) disorder which may affect your balance?

Yes (If Yes, please describe)

No

Date:

7. Have you ever been classified as having an auditory (e.g., inner ear disorder, concussion, vertigo, upper respiratory infection, etc.) disorder which may affect your balance or hearing?

Yes (If Yes, please describe)

No

Date:

8. Have you ever experienced an injury, for which you sought medical treatment, to your lower limb (e.g ankle, knee or hip)?

Yes (If Yes, please describe)

No

Date:

APPENDIX III – RESEARCH ETHICS CLEARANCE CERTIFICATE



Brock University
Office of Research Ethics
Tel: 905-688-5550 ext. 3035
Email: reb@brocku.ca

Health Science Research Ethics Board

Certificate of Ethics Clearance for Human Participant Research

DATE: 8/31/2021
PRINCIPAL INVESTIGATOR: BEAUDETTE, Shawn - Kinesiology
FILE: 20-366 - BEAUDETTE
TYPE: Masters Thesis/Project STUDENT: Aurora Battis
SUPERVISOR: Shawn Beaudette
TITLE: The acute effects of proprioceptive training of the low back using wearable sensor derived auditory biofeedback

ETHICS CLEARANCE GRANTED

Type of Clearance: NEW

Expiry Date: 8/1/2022

The Brock University Health Science Research Ethics Board has reviewed the above named research proposal and considers the procedures, as described by the applicant, to conform to the University's ethical standards and the Tri-Council Policy Statement. Clearance granted from **8/31/2021** to **8/1/2022**.

The Tri-Council Policy Statement requires that ongoing research be monitored by, at a minimum, an annual report. Should your project extend beyond the expiry date, you are required to submit a Renewal form before 8/1/2022. Continued clearance is contingent on timely submission of reports.

To comply with the Tri-Council Policy Statement, you must also submit a final report upon completion of your project. All report forms can be found on the Office of Research Ethics web page at <https://brocku.ca/research-at-brock/office-of-research-services/research-ethics-office/#application-forms>

In addition, throughout your research, you must report promptly to the REB:

- Changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
- All adverse and/or unanticipated experiences or events that may have real or potential unfavourable implications for participants;
- New information that may adversely affect the safety of the participants or the conduct of the study;
- Any changes in your source of funding or new funding to a previously unfunded project.

We wish you success with your research.

Approved:

Craig Tokuno, Chair
Health Science Research Ethics Board

Note: Brock University is accountable for the research carried out in its own jurisdiction or under its auspices and may refuse certain research even though the REB has found it ethically acceptable.

If research participants are in the care of a health facility, at a school, or other institution or community organization, it is the responsibility of the Principal Investigator to ensure that the ethical guidelines and clearance of those facilities or institutions are obtained and filed with the REB prior to the initiation of research at that site.