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Active and passive joint position sense on healthy hips

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Active and Passive Joint Position Sense of Healthy Hips

By

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Abstract

Hip proprioception has been tested on various populations, but there is limited research on healthy young adults. Primary assessments of proprioception for hip have been on joint position sense (JPS), but fewer studies have accomplished this in an unconstraint testing apparatus with angular repositioning tasks. Purpose of this study was to examine effects of active and passive repositioning on hip JPS in healthy young adults. It was hypothesized that active JPS error scores would be lower compared to passive JPS error scores. There was a total of 15 subjects in the study. Digitization of anatomical landmarks were used to create a virtual coordinate system to estimate hip joint center. JPS protocol consisted of three different conditions, passive with hip trolley, active with hip trolley and active without hip trolley. All conditions tested three different target positions of 30°, 45° and 60° degrees of hip flexion. The results of absolute and constant JPS error scores revealed that there was a linear decrease in average absolute error score, which elicited a decrease in levels of muscular control during flexion and accuracy of reposition targets (p=.001). The reduction of error score in passive JPS tasks may have allowed for subjects to concentrate on target angles more, because of less demand for joint stabilization. Unfortunately, most research contradicts the study's findings. Future research should focus on possible variables that further contribute to hip proprioception. Particularly studying the effects of lower back stiffening and fascial interactions with hip muscle activation.

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Literature Review

Proprioception

Charles Sherrington defined proprioception as taking sensations of the body's receptors being stimulated, then providing a response using mechanisms that are regulators of postural equilibrium, joint stability, and peripheral muscle senses (Sherrington, 1906; Lin et al., 2006; Proske & Gandevia, 2012; Sahlberg, 2014). Proprioception was later transformed into a more contemporary meaning of perception of the body's characteristics of movement, direction, and location in space and velocity via afferent and efferent neural pathways (Magill & Anderson, 2014). This system, both in the unconscious and conscious, is important for all major functions of the body (Hurley & Newham, 1998; Riemann & Lephart, 2002), especially for control and awareness of movement, known as kinesthesia, which will be discussed later (DiZio, Lackner & Champney, 2014; Han et al., 2016; Lin et al., 2006).

Somatosensory pathways account for afferent, efferent and central integration that aid with joint stability and coordinated movement (Riemann & Lephart, 2002; Sherrington, 1907). Somatosensory pathways are also involved in proprioception (Riemann & Lephart, 2002). Somatosensation comprises global sensation of the body via thermoreception, pain information from the periphery and mechanoreception (Riemann & Lephart, 2002); whereas proprioception focuses on afferent information from internal peripheral receptors that contribute to the maintenance of joint stability and appreciation of joint positions (Goble, 2016; Riemann & Lephart, 2002). To provide further understanding, proprioceptive information begins as a stimulus. This stimulus is detected by afferent mechanoreceptors that then, depending on type of receptor, is sent as action potential to the spinal cord; within consideration of conscious information going to the cerebral cortex and unconscious information going to the cerebellum

(Riemann & Lephart, 2002; Roijezon, Clark & Treleaven, 2015). The commands from the appropriate areas of motor output (somatosensory cortex), as efferent signals, are then sent back down the descending pathways to the proprioceptors for stimulus response (Riemann & Lephart, 2002; Roijezon, Clark & Treleaven, 2015). Proprioception is a small but important part of a continuous cycle of mechanoreceptor stimulation, neural transmission, merging of signals by the central nervous system (CNS), transmission of efferent signals, and muscle activation (Riemann & Lephart, 2002a; Lin et al., 2006; Kabbaligere, Lee & Layne, 2016). Altogether, a result with a responding force production that helps to provide timely and coordinated adjustments to environmental changes (Riemann & Lephart, 2002a; Lin et al., 2006; Kabbaligere, Lee & Layne, 2016).

Theories behind how the feedback control processes work with afferent signals coming from the receptors have minor differences (Proske, 2005). One theory states the feedback system that motor output is centrally derived (Proske, 2005). While the other theory states a process called efference copying, or corollary discharge (Proske, 2005; Roijezon et al., 2015). Efference copy describes that the brain compares what is happening to what should be happening, or exafference and reafference comparisons creating a negative (Bridgeman, 2007; Donaldson, 2000). However, most of the efference copy research is done on head and eye movement (Bridgeman, 2007; Roijezon et al., 2015), thus its regards to limb proprioception is limited.

Efference copy tends to also connect with sense of effort (Bridgeman, 2007; Proske, 2005, Prosk & Gandevia, 2012). With unknown origin of this mechanism, this remains with the conclusion that sense of effort does have a neurological mechanism, but whether its origin site is from afferent sensory feedback or central integration remains contested (Smirmaul, 2012; Proske, 2005; Proske & Gandevia, 2012). CNS driven sense of effort is explained with all motor commands originate in the motor cortex due to assumed predictions of movements the brain makes during sensory reception from afferent neurons (Smirmaul, 2012). With previous authors stating that the premotor cortex controls the primary somatosensory cortex via efference copy with no relation to sensory feedback (Simirmaul, 2012). The CNS theory of sense of effort is supported by results discussing that with the evidence of CNS commands being the dominate source for sense of effort brings further suggestions that sense of effort has its connections with kinesthesia (Allen & Proske, 2006; Proske & Gandevia, 2009). Although, kinesthesia is later discussed, its mechanisms from mechanoreceptors that are responsible for signal information that could be in contribution from force sense (sense of effort) (Proske & Gandevia, 2009).Which could indicate that for sense of effort to be centrally driven, that efference copy is a part the primary feedback controls for restoration and maintenance of stability of joints via posture, passive movement, active movement and resistance to movement (Riemann & Lephart, 2002).

Proprioceptive acuity is derived by the accurate sensory input of mechanisms to provide feedback from peripheral proprioceptors, vision and vestibular apparatus or balance (Hurley & Newham, 1998; Riemann & Lephart, 2002). In clinical research, proprioceptive acuity is the accuracy of peripheral proprioceptors' in detection of body segment position, movement and perception of external forces (Goble, 2016; Hurley & Newham, 1998). Some external factors that influence the proprioceptive acuity output are peripheral proprioceptive measurements such as limb preference, neural plasticity, age and muscle strength (Goble, 2016; Hurley & Newham, 1998; Riemann & Lephart, 2002). In addition, motor control objectives are to maintain and restore joint stability and equilibrium (Riemann & Lephart, 2002). Peripheral receptors (musculotendinous and capsuloligamentous) can significantly impact motor control of a joint (Riemann & Lephart, 2002). Thus, exclusion of visual and vestibular apparatus is preferred during repositioning tasks based on past findings of increased error rate compared to peripheral proprioceptors (Fitzpatrick & McCloskey, 1994). For this reason, proprioceptive acuity is measured by joint position matching tasks without assistance from vision and vestibular apparatus (Goble, 2016).

JPS and Kinesthesia

Joint position sense (JPS) and kinesthesia are subcategories of proprioception (Riemann & Lephart, 2002a; Han et. al, 2016; Hurley, Rees & Newham, 1998; Proske & Gandevia, 2012; Allen & Proske, 2006; Wright et. al, 2014). Both explain portions of movement sense and position sense; however, JPS and kinesthesia provide separate pieces of information for proprioception. That is promoted by angular excursion, stimulates joint and musculotendinous afferents that respond in more than one axis of rotation (Janwantanakul et. al, 2001). Kinesthesia and JPS are submodalities of proprioception with respect to less contemporary terms like posture, passive/active movement, and resistance to movement and muscular sense (Riemann & Lephart, 2002a; Sahlberg, 2014; Dover & Powers, 2003).

Kinesthesia is defined as conscious awareness and detection of joint movement (Voight, 1996; Sahlberg, 2014; Proske & Gandevia, 2012; Allen & Proske, 2006; Winter et. al, 2005) and is investigated by instruments of dynamometry and others like inclinometers (Voight, 1996; Suprak et. al 2016; Janwantanakul et. al, 2001; Dover & Powers, 2003). With these instruments, kinesthesia for example, is assessed then by measuring threshold to detection of passive motion (Lephart et al., 1997). JPS, on the other hand, is measured via reproduction of passive positioning and reproduction of active positioning (Lephart et al., 1997;). These are tests convey proprioceptive acuity and studies have specifically described findings of passive or active motion and in closed or open chain kinetic chain protocols in effects to JPS (Dover & Powers, 2003; Rogol, Ernst, Perrin, 1998).

JPS is described as the ability to perceive or sense a segment position relative to other parts of the body and in space via information relayed to the CNS peripheral mechanoreceptors (Dover & Powers, 2003; Suprak et. al, 2006; Sahlberg, 2014). JPS is often tested as an external task of position replication of a joint to measure proprioceptive accuracy (Dover & Powers, 2003; Suprak et. al, 2006; Sahlberg, 2014). Specifically, using absolute, constant and or variable error values from reproduction from a presented position (Voight et. al, 1996; Rogol, Ernst & Perrin, 1998; Janwantanakul et. al, 2001; Suprak et. al, 2006; Suprak et. al, 2007; Suprak et. al, 2016; Dover & Powers, 2003; Lin et. al, 2006). JPS error values are obtained using the differences of a target position and the attempted repositioning values (Pickard et al., 2003). In comparison, kinesthesia requires similar methods for thresholds of detection of passive motion (Proske & Gandevia, 2009). Both kinesthesia and JPS are ultimately equal in validity and reliability for use of interpreting proprioception.

There are two categories of mechanoreceptors supporting proprioception, musculotendinous and capsuloligamentous. Musculotendinous receptors, specifically, muscle spindles and Golgi Tendon Organs (GTOs), are located in the muscle and tendons, respectively (Suprak et al., 2006 & 2007; Voight et al., 1996). Capsuloligamentous receptors consist of Ruffini endings, Pacinian corpuscles, Golgi tendon-like endings and free nerve endings (Riemann & Lephart, 2002; Magill & Anderson, 2014), (with most research on Ruffini endings and Pacinian corpuscles). These receptors are mainly located in the joint capsule, ligaments, tendons and skin. Both capsuloligamentous and musculotendinous mechanoreceptors provide specific feedback regarding changes and adaptations to motions with respect to a given stimulus

(Riemann & Lephart, 2002; DiZio, Lackner & Champney, 2014; Suprak et. al, 2006 & 2007; Voight et. al, 1996; Janwantanakul et. al, 2001; Dover & Powers, 2003; Lin et. al, 2006). Together, these mechanoreceptors are fundamental components of proprioception, and will be discussed more fully in the following sections.

Mechanoreceptors: Capsuloligamentous

Capsuloligamentous receptors (Ruffini endings, Pacinian corpuscles and Golgi tendon-like organs) are housed within the capsules and ligaments of synovial joints. The structures of Ruffini endings and Pacinian corpuscles are both classified as skin receptors (Dover & Powers, 2003). They are two of four known skin mechanoreceptors, omitting Meissner corpuscles, and Merkel endings (Proske & Gandevia, 2012; Voight et. al, 1996) due to Ruffini endings and Pacinian corpuscles being the most prevalent in proprioception research. Both Ruffini endings and Pacinian corpuscles have been found within subdermal joint areas such as the knee and shoulder (Macefield, 2005). In addition, Golgi tendon-like organs are also located in these tissues and have similar behavior as Ruffini endings (Riemann & Lephart, 2002; Voight et. al, 1996). Thus, the Golgi tendon-like organs will be further discussed with findings of Ruffini endings.

Ruffini endings are classified as static receptors because of their low threshold and slow adaptation to stimuli, allowing them to discharge responses to a continuous stimulus (Dover & Powers, 2003; Lephart et. al, 1997). Slow adaptation is also seen in Golgi tendon-like organs (Voight et. al, 1996). Ruffini endings are activated by tissue stretch, slack and folding due to joint rotation (Proske & Gandevia, 2012; Voight et. al, 1996). Thus, these receptors are thought to facilitate joint sensations and position changes, in other words, joint position sense and kinesthesia (Lephart et. al, 1997). Previous research findings indicate that these receptors primarily respond to limits of angular excursion, during active and passive ROM (Macefield, 2005; Voight et. al, 1996). The receptors' behavior could suggest that Ruffini endings, as well as other slow adapting capsuloligamentous receptors (Golgi tendon-like organs), are the most involved with joint position sense and kinesthesia in end ranges of motion than was assumed before based on previous findings (Collins et al., 2005; Macefield, 2005; Proske & Gandevia, 2012). Collins and colleagues illustrated that during stretch and vibration trials of MCP, elbow and knee joints, an increase of perceived knee flexion with vibration and stretch than vibration alone. Thus, the stimulus that targeted musculotendinous receptors, vibration, was not as sensitive with joint position than in combination with capsuloligamentous receptors (Collins et al., 2005).

Pacinian corpuscles are receptors that input information within the joint capsule and synovial membrane (fibrosum layer) (Macefield, 2005). Pacinian corpuscles also have a slightly different filtering characteristic than Ruffini endings; allowing brisk mechanical transients to generate a stimulus, due to the receptors' rapid adaptation to stimuli (Macefield, 2005; Proske & Gandevia, 2012). These receptors are stimulated by both compression stimuli and stretch (Voight et. al, 1996; Macefield, 2005; Proske & Gandevia, 2012). Sensations such as compression and stretching in tissues about a joint are detected when the joint is passively or actively moving about the axis of rotation, being most active at the end ranges of motion (Voight et. al, 1996). Previous research has considered the end ranges of motion to be the height of sensitivity when parent tissue is most deformed (Amiri-Khorasani et. al, 2011; Proske & Gandevia, 2012; Voight et. al, 1996).

Mechanoreceptors: Musculotendinous

Musculotendinous mechanoreceptors (i.e. muscle spindle, GTOs) are considered main components of detection in muscular deformation, especially in midranges of motion, where the capsuloligamentous receptors are least sensitive (Janwantankul et al., 2001; Suprak et al., 2005; Proske & Gandevia, 2012), though there is controversy with what mechanoreceptors are the greatest contributors (Collins et al., 2005). Nevertheless, there has been evidence of these mechanoreceptors being the primary informers of proprioceptive information with regards to joint position sense and kinesthesia (DiZio, Lackner & Champney, 2014; Hurley & Newham, 1998; Sahlberg, 2014; Sherrington, 1907; Suprak et al., 2007). This evidence includes acuity, feedback and joint stability characteristics of musculotendinous mechanoreceptors (Hurley & Newham, 1998; Riemann & Lephart, 2002; Macefield, 2005; Sahlberg, 2014). Particularly being dynamic contributors in detections of forces conducted by muscles and tendons (Hurley & Newham, 1998; Riemann & Lephart, 2002; Macefield, 2005; Sahlberg, 2014).

Muscle spindles, owing to their location in the muscle, identify muscle lengthening along with the changes in length of the muscle fibers with regards to velocity of the contraction or stretch taking place (Hurley & Newham, 1998; Magill & Anderson, 2014; Voight et al., 1996, DiZio, Lackner & Champney, 2014; Suprak et al., 2007; Proske & Gandevia, 2012). Within the muscle spindle comprises a fiber capsule; intrafusal fibers and stretch receptors (Macefield, 2005). These intrafusal fibers have adaptive properties and are individually controlled by the CNS (Hospod, 2007). By association, CNS has adaptive properties in regards to the muscle spindle (Hospod, 2007). Together, stretch receptors are housed by the intrafusal fibers as they detect movement signaled by the velocity component of the response to length change (Proske & Gandevia, 2009 & 2012). This allows for detection of heaviness and force with high threshold response, with exception of the inability to detect force generation of neighboring muscles (Macefield, 2005). Furthermore, intrafusal fibers are arranged in parallel to the main force-generating extrafusal muscle fibers, which disables them from encoding forces generated by contraction of the muscle, but sensitive to stretch and lengthening of the fibers (Macefield, 2005). Even so, proprioceptive input from muscle spindles has cumulative sensory information via population coding, by intrafusal components of primary stretch receptors (DiZio, Lackner & Champney, 2014; Proske & Gandevia, 2009; Macefield, 2005).

GTOs, located in the musculotendinous junction, detect changes in tension and force being placed on the tendons, whether it be active or passive (Magill & Anderson, 2014; Macefield, 2005; Voight, 1996, Riemann & Lephart, 2002; Suprak et al., 2007; Proske & Gandevia, 2012; Gregory et al., 2002; Jami, 1992). When tension is developed in the tendon, slack is taken out of the collagen fibers, which causes them to apply pressure on active 1b afferent fibers of the GTO (Voight, 1996; Riemann & Lephart, 2002; Suprak et al., 2007; Macefield, 2005; Jami, 1992). GTOs are also described to have functions for sensations of heaviness and force and as limit detectors with high threshold response, as do muscle spindles (Proske & Gandevia, 2012; Voight et al., 1996). These characteristics could then relate to sensitivity being enhanced at mid-ranges of motion as described in the fingers (Proske & Gandevia, 2012), due to interphalangeal joints being composed of tendon, collagen and fascia (Macefield, 2005).

GTO contribution to position sense has also been demonstrated in recent literature that examines responses to muscle activation and stretching (Gregory et al., 2002; Magill & Anderson, 2014; Macefield, 2005; Voight, 1996, Riemann & Lephart, 2002; Suprak et al., 2007; Proske & Gandevia, 2012). With eccentric forces, GTOs have been observed maintaining and even increasing sensitivity in the ability to signal muscle tension (Gregory et al., 2002), even after fatiguing protocols (Proske & Gandevia, 2012; Gregory et. al, 2002). This observation indicates that sensitivity of GTOs within musculotendinous junction can provide to other receptors (e.g. motor neurons) with summation of forces that are then applied (Macefield, 2005; Riemann & Lephart, 2002; Riemann & Lephart, 2009) and remains consistent and unimpaired by fatigue and muscle fiber damage during activity (Walsh et al., 2004). This ability of counteracting fatigue would be critical for injury prevention and contribution to proprioceptive acuity (Riemann & Lephart, 2009).

It has been postulated that tendon organs are a part of a larger scheme for “sense of effort”. This phenomenon has been seen when a segment is not supported during bouts of position sense protocols (Winter et al., 2005; Walsh et al., 2004; Blum et al., 2017). Studies suggest that when a limb is unsupported during JPS protocols, the force of gravity allows for a larger signal from musculotendinous mechanoreceptors (Jami, 1992; Gregory et al., 2002). There has also been continued discussion about a force-effort relationship of muscles due to the suggestion of GTOs being primary advocates for sense of effort (Walsh et al., 2004; Gregory et al., 2002; Proske & Gandevia, 2009; Jami, 1992). Sense of effort is also a tactic that the body uses to maintain a position, especially in an example of accomplishing a repositioning task after fatiguing protocol (Walsh et al., 2004). Walsh and colleagues’ results follow the same findings as an increase of sensitivity to muscle tension that has been previously discussed (Gregory et al., 2002, Blum et al., 2017; Jami, 1992). A sense of effort relies mainly on the signal strength being sent to afferent motor neurons (Winter et al., 2005; Gregory et al., 2002), which is a similar signal outcome from muscle tension that is being detected at the musculotendinous junction (Gregory et al., 2002). Thus, studies suggest that GTOs specifically provide this type of information of movement sensation. However, the sense of effort mechanism and its relations to joint position sense requires further investigations to understand the roles of mechanoreceptors and central mechanisms (Macefield, 2005).

Motor Neurons

Three types of known motor neurons innervate muscle; with the larger in diameter type being alpha (α), and the smaller being beta (β), and gamma (γ)/fusimotor (Hospod, 2007; Macefield, 2005; Proske & Gandevia, 2012). Specifically, α-motor neurons innervate extrafusal fibers, γ-motor neurons innervate intrafusal fibers of the muscle spindles and β-motor neurons innervate both β and γ muscle spindle fibers, especially low threshold motor units (Proske & Gandevia, 2012). The α-motor neurons are in direct interaction with the skeletal muscle due to the innervation of the extrafusal component of the muscle, which also provides much of the force generated (Magill & Anderson, 2014; Proske, 1997; Proske & Gandevia, 2012; Lephart et. al, 1997). The β and γ-neurons enable an afferent feedback system to the CNS, providing a connection from extrafusal to intrafusal (α to β/γ – motor neurons), based on the nuclear bag model (Macefield, 2005; Magill & Anderson, 2014; Proske, 1997; Proske & Gandevia, 2012). This model can explain why γ motor neurons allow for spindle adjustment of sensitivity, supporting the α motor neurons by its respective innervations at the polar region of the nuclear bags (Lephart et. al, 1997; Proske & Gandevia, 2012). Findings suggest that α and γ motor neurons assist with muscle spindles sensitivity, through a phenomenon called α-γcoactivation (Hospod, 2007, Suprak et. al, 2007). With consideration that γ – motor neurons are in a linkage in coordination of the extrafusal as well as intrafusal (muscle spindle) components (Suprak et. al, 2007; Macefield, 2005, Michelson & Hutchins, 1995).

Although studies report the greatest acuity occur at end ranges in constrained models (Han et. al, 2016; Janwantanakul et. al, 2001), there is disagreement with studies using unconstrained models (Amiri-Khorasani et al., 2011; Arvin et. al, 2015; Ishii et. al, 1999; Onishi et. al, 2017; Suprak et. al, 2006; Suprak et. al, 2007; Suprak et. al, 2011; Pickard, 2003; Stillman et. al, 1998). In depth, when a joint is unconstrainted, the limb must be supported against gravity, which requires the muscle spindles to remain sensitive via muscle activation (Suprak et al., 2007). Research further supports unconstrainted model so that the intrafusal muscle spindle sensitivity is maintained throughout an imposed stretch or force generation even in shortening (Suprak et. al, 2006; Suprak et. al, 2007; Hospod, 2007; Macefield, 2005; Durbaba et. al, 2001 & 2003). These previous studies display that muscle spindles activity often correlate with muscular activity via motor neuron coactivation (Hospod, 2007).

Structures of the hip

Considered to be a true ball-and-socket joint, the hip allows all three planes of rotation and translation (Jaffar, Abass, & Ismael, 2006; Powers, 2010; Retchford et al., 2013; Schuenke et. al, 2014). The acetabulum of the hip and femoral head is incased in a complexity of structures varying from the labrum cartilage, ligaments, muscles (Torry et al., 2006) and even nerve innervations (Kim & Azuma, 1995; Alzaharani et al., 2014; Haversath et al., 2013; Schuenke, Schulte, Schumacher; 2014). The bony anatomy of the hip has contributions from three regions of the pelvis (ilium, ischium and pubis) and the femur (femoral head) (Torry, et al., 2006); which then provide attachment sites for each muscle involved in hip actions.

Previous studies have discussed a multitude of muscles that are in proximity of the hip joint and or are involved in hip movement, stability and or functionality. The muscles listed are: Gluteus medius, gluteus minimus, gluteus maximus, adductor magnus, adductor longus, adductor brevis, pectineus, iliacus, psoas, quadratus femoris, gemelli (inferior and superior), piriformis, rectus femoris, semimembranosus, semitendinosus, biceps femoris, gracilis, sartorius, obturator internus and externus, and tensor fasciae latae (TFL) (Retchford et al., 2013; Torry et al., 2006; Wickiewicz et al., 1986, Schuenke, Schulte, Schumacher; 2014; Soderberg & Andrews, 1986).

Most muscles mentioned have ultimately been conclusive about their roles in hip joint stability, movement and functionality (Schuenke, Schulte, Schumacher; 2014; Soderberg & Andrews, 1986). Fundamental studies have also categorized them by motions that each muscle participates in (Soderberg & Andrews, 1986) along with mechanical moments, or lines of action (Soderberg & Andrews, 1986; Wickiewicz et al., 1986). Specifically, quadratus femoris, obturator internus, externus and gemilli are considered rotator cuff muscles of the hip (Retchford et al., 2013). Yet, there are still specific muscles that have been less definitive than most and primarily assumed functions by pinnation and cross-sectional area (CSA) (Torry et al., 2006; Wickiewicz et al., 1986, 1990). These muscles are piriformis, pectineus and iliopsoas (Giphart et al., 2017). Although textbooks describe these muscles to have specific roles (Schuenke, Schulte, Schumacher; 2014), recent studies have investigated these muscles in depth, in attempts to understand the behavior of these muscles in multiple scenarios (Giphart et al., 2017; Leung et al., 2014). Giphart and colleagues (2017) revealed a specific role of the pectineus being active during hip flexion (Giphart et al., 2017). The pectineus has been noted as a primary muscle for hip external rotation (Schuenke, Schulte, Schumacher; 2014). Hypertrophy of the piriformis in a study by Leung and colleagues (2014) demonstrated that resistance of internal rotation and increase CSA of the piriformis after neuromuscular training was completed.

The hip also contains major ligaments and tendons that provide passive stability, dynamic stability and dynamic motion (Kadaba et al., 1990; Retchford et al., 2013). Although not all structures are mentioned in this review (Torry et al., 2006), the structures that seem to be involved in hip proprioception are the ligamentum teres or capitis femoris (LCF), transverse acetabular ligament (TAL), acetabular labrum and other nerve innervations (Kilicarslan et al., 2015; Birnbaum et al., 1997; Leunig et al., 2000; Retchford et al., 2013). In fact, the LCF is a part of growth and development of the femoral head due to vascularization in prepubescent ages (Sarban et. al, 2007; Bardakos & Villar, 2009). The labrum seems to be designed to provide a deepened socket for the femoral head (Torry et al., 2006). With a “U” shape, it also seems to provide a similar purpose as the menisci to the knee and is comprised of various collagen types (Mason, 2001).

Previous studies have examined TAL, LCF and labrum for evidence of mechanoreceptor existence (Desteli et al., 2014; Gerhart et al., 2012; Kilicarslan et al., 2015; Retchford et al., 2013). Although minimal clear evidence of somatosensory afferent nerve endings are found (Dehao et al., 2015; Murtali et al., 2004), cadaveric and surgical research revealed hip samples to have significant amounts of type IVa nerve endings, or free nerve endings (Sarban et. al, 2007; Bardakos & Villar, 2009; Kapetanakis et al., 2017; Kilicarslan et al., 2015; Leunig et al., 2000; Retchford et al., 2013; Voight et. al, 1996). With suggestion that these structures have a proprioceptive role in the hip via nociception (Gerhardt et al., 2012; Kapetanakis et al., 2017; Moraes et al., 2011).These studies have also confirmed other mechanoreceptors similar to Ruffini endings and GTOs in the hip capsule (Gerhardt et al., 2012; Kapetanakis et al., 2017; Moraes et al., 2011).

Free nerve endings (FNE), although not discussed much in proprioceptive literature, are displayed as pain receptors for a joint, known as nociception (Sarban et. al, 2007; Bardakos & Villar, 2009; Kilicarslan et al., 2015; Retchford et al., 2013). FNE have also been located in the same tissues as other mechanoreceptors (Kim & Azuma, 1995; Lewis et al., 2006; Riemann & Lephart, 2002). Thus, these receptors could play a role in sensory functions in the hip by using pain as a detection for unsafe ranges of motion. Voight et. al (1996) suggested that FNE are aroused by forceful rotation stimulus, which can confirm Kilicarslan and colleagues (2015) findings of A-delta mechanoreceptors and group C polymodal nerve endings within the acetabular labrum and classifying them as sensory fibers. These pain receptors would help alert and prevent the hip from mechanical tissue damage (Kilicarslan et al., 2015; Leunig et al., 2000). FNE in the acetabular labrum allow for the joint capsule to detect femoral head translation and extreme ranges of motion to possibly enhance proprioception and joint stability (Kapetanakis et al., 2017; Retchford et al., 2013).

FNE in other components of the joint capsule enhance the proprioceptive ability of mechanical properties such as the LCF during dynamic tensile loads, much like the ACL for the knee (O'Donnell et al., 2018). However, other authors postulate that mechanical abilities of the LCF play more of a role with passive stabilization and that the ligament is most stressed during external rotation of the hip (Retchford et al., 2013). Nerve innervations found in the TAL, LCF and labrum also suggest that these structures allow for some somatosensory awareness (Birnbaum et al., 1997). Nevertheless, the role of the LCF, TAL and labrum have promising connections of nociception and proprioception with consistent findings of FNE and nerve bundles within the hip (Bardakos & Villar, 2009; Kilicarslan et al., 2015; Leunig et al., 2000; Sarban et. al, 2007).

Shoulder versus Hip

In comparison to a modified ball-and-socket joint, the shoulder, the hip allows the same degrees of freedom as the shoulder. However, due to the more unstable nature of the interactions of the glenoid labrum, ligamentous support, and humerus, there is more ROM at the shoulder than there is at the hip (Jaffar, Abass, Ismael, 2006; Schuenke et. al, 2014; Bardakos & Villar, 2009). Moreover, the hip is more stable due to its naturally deeper socket fitting with the acetabulum and femoral head, which restricts extreme ROM (Jaffar, Abass, Ismael, 2006;

Mason, 2001; Schuenke et. al, 2014). The similarities between the shoulder and the hip were further examined by Jaffar and colleagues (2006), who compared structural and functional properties of cadaveric bones, ligaments and muscles that make up these two joints. Their findings provided more evidence of differences in between shoulder and hip, but also accentuated the similarities of both joints, by an observation of the hip allowing for greater tension and forces applied to the structure before subluxation or complete dislocation (Jaffar, Abass, Ismael, 2006). With comparison to the shoulder, and same degrees of freedom, the hip has greater bony constraints for purposes that seem to be for prevention of subluxation and hypermobility using balance and stabilization (Arvin et al., 2015; Jaffar, Abass & Ismael, 2005; Bejaminse et al., 2009; Ishii et al., 1999; Pickard et al., 2003; Retchford et al., 2013; Wingert et al., 2014).

In addition to stabilization, intracapsular and atmospheric pressure changes encourage the shoulder to have greater stabilization from its joint capsule (Kumar & Balasubramaniam, 1985; Retchford et al., 2013). This is observed as decreased occurrences of subluxation when capsular pressure was released (Kumar & Balasubramaniam, 1985). This effect of released pressure was not seen with the hip (Wingstrand, Wingstrand & Krantz, 1990). With the hip having greater joint contact surface of the labrum than the shoulder, allows for greater joint stability during traction even without capsule pressure and labrum support (Jaffar, Abass & Ismael, 2005; Wingstrand, Wingstrand & Krantz, 1990).

Deep muscles of the hip, such as obturator internus and externus, quadratus femoris and the gemelli, are what can be considered rotator cuff muscles of the hip (Retchford et al., 2013). The shoulder also has this muscular structure, naming rotator cuff muscles, teres minor, infraspinatus, supraspinatus, and subscapularis (Jaffar, Abass, Ismael, 2005). There is evidence of deep hip muscles providing similar type of stability that is seen from rotator cuff muscles in the shoulder. The functionality of the deep hip muscles is the same as the rotator cuff muscles of the shoulder, but design, cross sectional area (CSA), moment arms and pinnation has some differences (Neumann, 2010) that suggest that the rotator cuff muscles of the hip play a role in hip joint stiffness, passive stability and proprioception (Retchford et al., 2013; Torry, 2006).

Other studies that examine knee mechanics find that weak hip muscles can cause instability in the knee, which would allow for valgus motions to occur; increasing chances of injury (Benjaminse et al., 2009; Boling et al., 2009). This topic of knee injury with weak hip muscles has been researched extensively (Homan et al., 2013; Powers, 2010;), leading into a conclusion that because of the increased demand for stability in the hip is simply the nature of these muscles. Therefore, more investigation of proprioceptive behaviors of the hip are required for a complete comparison of the shoulder and hip.

Specific populations on proprioception and JPS

Investigational topics of the hip have been listed as nerve and mechanoreceptor innervation, ligament and structural characteristics. Tested populations include arthritic patients, athletes of novice, amateur, and elite levels, hip arthroplasty patients, older adults (Adamo, 2007; Arvin et al, 2015; Benjaminse et al., 2009; Lin et al., 2006; Moraes et al., 2011; Onishi et al., 2017; Wright et al., 2014; Pickard et al. 2003). For instance, athletes have been seen to display enhanced hip joint position sense compared to those of novice skill level or sedentary individuals (Lin et. al, 2006). The repositioning error value for JPS was dependent on group skill level, relating experience to decreased joint position sense error (Lin et al., 2006, Muaidi et al., 2008). There have also been studies that have applied proprioceptive and balance exercises to see if there are changes in joint position sense (David et al., 2019; Daneshjoo et al., 2012; Diracoglu et al., 2005). David and colleagues (2019) observed small improvements in absolute error just with foam rolling immediately before. These observations have been explained by neuropathological adaptations and enhancement of sensation for neuromuscular coordination from sport specific skills learned over time (Bressel et al., 2007; David et al., 2019; Lin et al., 2006; Nagai et al., 2013).

For special populations, common studies tend to be with arthroplasty and arthritic patients (Ishii et al., 1999; Onishi et al., 2007; Moraes et al., 2011). Subjects with unhealthy hips have been reported to not have major differences of JPS ability, but comparing to similar studies, there are losses in proprioception and mechanoreceptor composition with age (Kaplan et al., 1985; Onishi et al., 2017; Wingert et al., 2014). This decline in JPS and kinesthesia has been exhibited in both active and passive movements, focused within planes of rotation for the hip joint (Goble, 2010; Hurley, Rees & Newham, 1998; Onishi et al., 2017). This finding could indicate that injury may not fully impede on JPS acuity, but age might. However, there remains disagreement of a possible age-related decrease in proprioception (Ishii et al., 1999; Pickard et al., 2003).

Benjaminse and colleagues (2009) remains to have the most current study of healthy hip JPS. Healthy individual data would provide further understanding of proprioceptive and neuromuscular relationships in the body as to how the brain communicates with joints. It was warranted that to continue doing active JPS to investigate more of a possible standardization for what error scores can be used in a clinical setting (Benjaminse et al., 2009). Specifically, aiding with progress data for rehabilitation, providing that the repeatability of the JPS and error scores are valid. With JPS being an accessible application on a cell phone (Edwards et al., 2016), the use of the error scores per person may help with neuromuscular and proprioceptive decline in age and possible connections with athletic performance (Lin et al., 2006; Lin et al., 2009).

A possible cause to this controversy in research could be the inconsistency of methodology used for angular repositioning measurements (Goble, 2010; Elangovan, Herrmann, & Konczak, 2014; Han et al., 2016). A lack of regulation of how JPS is measured can create differences in findings among literature. There are previous validation studies for JPS (Arvin et al. 2015; Benjaminse et al., 2009; Edwards et al., 2016; Nussbaumer et al., 2010), but there still no true conclusion of proper methodology. In addition, choices in equipment used to measure JPS are not congruent, with variations of equipment from goniometry (Kaplan et al., 1985; Nussbaumer et al., 2010; Onishi et al., 2017) and dynamometry (Benjaminse et al., 2009) to motion capture systems (Amiri-Khorasani, Osman & Yusof, 2011; Arvin et al., 2015). Nevertheless, most methods are currently categorized as constrained models for measurement of JPS. A constrained model can be defined as any apparatus that causes resistance of motion or encasement of the target limb (Suprak et al., 2006). A constrained model also limits findings, understanding that the restriction from the apparatuses used manipulates how a subject detects join position from tactile cues (Suprak et al., 2011) and increased muscular effort (Voight et al., 1996; Suprak et al., 2006). These methods of constrained versus unconstrained could explain the increase in sensitivity/acuity of the joint because of interpreted motion by the joint as an external load (Suprak et. al, 2007) or from end ranges of motion (Janwantanakul et al., 2001). This further promotes methods on measuring acuity during active and passive using an unconstrained model (Voight et. al, 1996; Rogol, Ernst & Perrin, 1998; Suprak et. al, 2006; Suprak et. al, 2007; Suprak et. al, 2016. There are previous studies that evaluation ROM and JPS using unconstrained apparatuses (Edwards et al., 2016; Suprak et al., 2006; Suprak et al., 2007; Pickard et al., 2003), and find different results, but very few are focused on the hip joint. Therefore, the purpose of this study was to examine the effects of active and passive positioning of the hip on averages of absolute error and variable error on healthy young adults. It was hypothesized that there will be a decrease in absolute error and variable error in active positioning compared to passive. It was also hypothesized that an active unconstrained assessment would have a reduction of repositioning error than constrained JPS assessment.

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Introduction

In many sports, hip injuries are commonly observed among athletes of all ages (Kerbel et al., 2018). High impact sports such as soccer and football, require the body to engage in rapid acceleration and deceleration along with cutting and quick changes in direction (Prather, 2014). In athletes of all ages, the most common hip injuries in recent years have been femoroacetabular impingement (FAI) (5-6%) and snapping hip syndrome (5-10%) (Prather, 2014; Keogh & Batt, 2008). The significant amount of force upon the hip joint from activities over time could lead to bone degradation and decreased performance and could eventually progress to joint disorders such as osteoarthritis (Keogh & Batt, 2008). For rehabilitation, clinicians often recommend intervention that focuses on proprioception and maintenance of range of motion (ROM) in attempts to alleviate the symptoms of joint disorders (Kapetanakis et al., 2017; Lin et al., 2009).

Proprioception has transformed into a contemporary definition of awareness and sensation of joint and segment position, movement direction, and movement speed via afferent neural pathways (Magill & Anderson, 2014; Riemann & Lephart, 2002a; Lin et al., 2006; Kabbaligere, Lee & Layne, 2016). Afferent signals provide feedback to the brain needed to respond to environmental changes with force production that aids with timely and coordinated adjustments (Riemann & Lephart, 2002a; Lin et al., 2006; Kabbaligere, Lee & Layne, 2016). These signals originate from specialized neural transducers (i.e., receptors) called mechanoreceptors, or proprioceptors, that convert stimuli to action potentials for transmission in the central nervous system (CNS) (Roijezon, Clark & Treleaven, 2014). Categories of proprioception are divided into several submodalities. Kinesthesia, or sense of motion and direction of motion; joint position sense (JPS), ability to detect limb position in space; and sense of effort or tension

(Dover & Powers, 2003). JPS is the most common for proprioceptive measurement (Dover & Powers, 2003; Han et. al, 2016; Proske & Gandevia, 2012; Allen & Proske, 2006). This breakdown of categories has provided researches to understand proprioception and its application to rehabilitation and injury prevention.

Research on assessment of hip proprioception has increased over the years, and results of these studies have which suggested that free nerve endings (FNE) may be involved in proprioception, along with mechanoreceptors in the hip (Sarban et. al, 2007; Bardakos & Villar, 2009; Kilicarslan et al., 2015; Retchford et al., 2013) even after arthroscopy (Kapetanakis et al., 2017). Free nerve endings (FNE) have been known to register pain or nociception (Sarban et. al, 2007; Bardakos & Villar, 2009; Kilicarslan et al., 2015; Retchford et al., 2013). Previous research from Voight and colleagues (1996) suggests that FNE are and stimulated by forceful rotation at the hip, with the feedback perhaps arising from densely innervated ligamentum teres (LCF), transverse acetabular ligament (TAL) and acetabular labrum (Birnbaum et al., 1997; Kilicarslan et al., 2015; Leunig et al., 2000; Retchford et al., 2013). Thus, FNE could be part of position sense abilities in the hip. For example, greatest mechanical stress of the hip is during external rotation (Retchfor et al., 2013). Which LCF would play a role in passive stabilization (Retchford et al., 2013).

Possible causes to controversy in research on JPS could be related to inconsistencies in methodology during angular repositioning measurements (Goble, 2010; Dover & Powers, 2003; Elangovan, Herrmann, & Konczak, 2014; Han et al., 2016). Although there are validation studies (Arvin et al. 2015; Benjaminse et al., 2009; Edwards et al., 2016), lack of consistency in measurement of JPS could be leading to differences in findings among literature. For instance, a previous study showed results that favored active position sense testing over passive position sense (Erickson & Karduna, 2012; Hung & Darling, 2012; Friement et al., 2006). It has been explained in previous studies that passive JPS tasks are often used rehabilitation settings (Erickson & Karduna, 2012; Kwon et al., 2013; Lephart et al., 1997). However, previous research that has compared active and passive JPS often favor active over passive JPS (Erickson & Karduna, 2012; Hung & Darling, 2012; Friement et al., 2006). These studies discuss that the reduction of error in reproducing positions can be explained by heightened muscle activation when subjects are required to move their own limb rather than being assisted (Erickson & Karduna, 2012). Currently, common procedure for JPS data collections have the subject be attached to the equipment that quantifies the origin and reproduced positions that then provide a value that represents the differences between the two positions called error scores. Unfortunately, some apparatuses have been seen to constrain joint range of motion (Han et. al, 2016; Janwantanakul et. al, 2001).

Another factor possibly adding to controversy are inconsistency in choices of equipment used to measure JPS. Previous studies have used a variety of equipment such as goniometry (Kaplan et al., 1985; Onishi et al., 2017), dynamometry (Benjaminse et al., 2009), motion capture systems (Amiri-Khorasani, Osman & Yusof, 2011; Arvin et al., 2015), inclinometers (Dover & Powers, 2003), and electromagnetic tracking devices (Suprak et al., 2006). Edward and colleagues (2016) recently developed a software application for the iPod Touch that combines accelerometry and gyroscope to eliminate tactile sensation and allow for natural range of motion. Nevertheless, most methods are currently categorized as constrained models. Thus, do not address the tactile sensations (Suprak et al., 2011) and or restraining the joint from naturally arriving at a target position, which could limit findings. There are previous studies that evaluated ROM and JPS using unconstrained apparatuses (Edwards et al., 2016; Suprak et al., 2006; Suprak et al., 2007;

Pickard et al., 2003), and find different results than of constrained models, but very few are focused on hip JPS (Benjaminse et al., 2009; Leardini et al., 1999).

Benjaminse and colleagues (2009) remains to have the most applicable study of healthy hip JPS. Healthy individual data would provide further understanding of the relationship between proprioception and muscle activation. Author suggested that JPS research should continue to aim for standardization; specifically, utilization of error scores as reference to what should be normal (Benjaminse et al., 2009). Standardization would provide stronger repeatability and validity of JPS and allow for greater understanding of error scores. Therefore, the purpose of this study was to examine the effects of active and passive positioning of the hip on average absolute JPS error and constant JPS error on healthy young adults. It was hypothesized that there will be a decrease in absolute error and constant error scores in active repositioning compared to passive.

Methods

Subjects

There were 15 (8 female, 7 male) healthy individuals participated in the study. Subject demographics are described in Table 1. The research protocol was verbally reviewed by the researcher, as well as a written informed consent provided for each participant to read and sign. This informed consent form, as well as the protocol used in the study, was approved by the Western Washington University review board for Human Subjects. Subjects that were included in the study had no previous history of lower back/hip pain, injury or surgery that required professional healthcare intervention. Exclusion criteria included low back/hip pain and or surgery within the last year.

Instrumentation

The Polhemus Liberty (Colchester, VT), integrated with The Motion Monitor™ software (Innovative Sports Training, Inc., Chicago, IL) was used to track hip angles throughout the protocol at a sampling rate of 240 Hz. The Polhemus unit consisted of a transmitter, two receivers, and a digitizer. The digitizer was used to determine location and orientation of the sensors in space relative to the transmitter (Pickard et al., 2003; Suprak et al., 2006; Swinnen et al., 2014). The receivers were placed about 2.54 cm above spinous process of the first sacral vertebrae and midthigh of the dominant leg. Midthigh was defined as equal distance between the greater trochanter and lateral femoral epicondyle of the dominant leg. After placement of the receivers, palpation and digitization of L5/S1 joint space, left/right medial and lateral femoral epicondyles was completed. The joint coordinate system for the femur and pelvis has been established previously by the Terminology committee of the International Society of Biomechanics (ISB) (Wu et al., 2002) and is integrated into The Motion Monitor™ software. Joint coordinate systems were established using a rotation method from Euler angle sequence: flexion/extension, internal/external rotation, and ab/adduction. Per these guideline and software setup, a 3D joint center was established. Once all trials were recorded, hip angles were calculated using an Euler angle sequence in accordance with the recommendation of the ISB (Wu et al., 2002). Leg dominance was determined by the preferred take-off leg for jumping (Benjaminse et al., 2009).

To limit the effects of gravity in the plane of motion (sagittal) during passive trials, subjects had a specialized hip trolley (Figure 1) attached to the ankle with an air splint for stability. The trolley and air splint were attached in such a way that it would not inhibit or manipulate subjects' hip mobility or sensitivity. The hip trolley would allow decrease muscle activation during passive trials as encouraged by previous studies (Suprak et al., 2006). In addition, subjects' legs were also placed in the hip trolley for an additional active condition to eliminate the effect of tactile cues in one condition versus the other in addition to limiting the effects of gravity.

JPS Protocol

Once subjects were digitized and set up with two landmark sensors, sacrum and thigh, subjects were instructed on how positioning and repositioning for both active and passive movements were to be done (See Figure 1). Subjects were positioned to lay on their nondominant side and have their head rested on their arm in recovery position after placement and digitization of receivers and hip joint centers, and then blindfolded. Subjects then proceeded with verbal instructions and were allowed to practice until they felt comfortable with the protocol during a metronome count. To prevent contribution of internal and external rotation of the hip, subjects were instructed to keep their toes pointed forward and the knee in natural full extension. Neutral or starting position of the tested leg was defined as full hip extension and being in line with their other leg while subjects remained on their side during trials. Subjects were also allotted a one-minute rest between active trials and 30 seconds between passive trials to reduce the effects of fatigue.

All trials began with the hip in the neutral position (0° of hip flexion). Neutral was described to the subjects as a 'straight line' from their shoulder to their ankle. In the passive trials, the subject's hip was then moved into flexion in the sagittal plane to the target position by the researcher. This was accomplished at a velocity of approximately 10°/sec. This pace was determined previously by metronome, and leg positioning was guided by the computer output displaying the hip flexion angle. Once the target angle was reached, it was held for three seconds, while the subjects were instructed to concentrate only on the position of the hip in the sagittal plane. The researcher then brought the hip back to the neutral position at approximately the same velocity. The hip was held in the neutral position for 3 seconds. Then, the researcher began moving the hip into flexion at approximately the same velocity while the subject attempted to replicate the target position by indicating to the research when they felt that they matched the target angle, at which point researcher was instructed to “stop”. Subjects repeated this process for three trials each at target angles of 30°, 45°, and 60° of flexion for a total of nine total trials. The presentation of these trials was presented randomly via a balanced latin square design.

For active trials, subjects were verbally instructed to move into hip flexion at approximately the same pace as for the passive trials. Active trials were also done with and without hip trolley. Having both sets of trials will allow the study to fully investigate the effects of muscle activation on joint position sense tasks. Subjects were asked to actively flex their hip, and when they are within three degrees of the target position, subjects were told to “hold” in the position for three seconds while concentrating only on the position of the hip. After three seconds, subjects were told to ‘come back’ to the neutral position. After three seconds in the starting neutral position, subjects were instructed to ‘reproduce’ the position as closely as possible, by flexing the hip until they felt they had returned to the target position. There, they remained for a full second. Subjects repeated this process for three trials each at target angles of 30°,45°, and 60° of flexion for a total of nine trials. As with the passive trials, these trials were randomly presented via a balanced latin square design.

Data Analysis

Three-dimensional hip kinematics were calculated via transformation matrices, using the Motion Monitor™ software (Innovative Sports Training Inc., Chicago, IL) for all active and passive position replication conditions. The output values (hip flexion angles) were then further processed with a custom-written MATLAB (The MathWorks, Inc., Natick, MA, USA) software. Hip flexion angles in both target and replicated positions were calculated, and then compared. The constant error was calculated by subtracting the hip flexion angle in the target position from the replicated position. Therefore, a positive constant error indicated that the hip was more flexed in the replicated position (overshot) as compared to the target position. This constant error was then averaged across the three trials for each target angle. Absolute error for each target angle was calculated as the absolute value of the constant error and averaged across all three trials for each target position. A successful trial of 'hitting' the target position was within three degrees of the target position (e.g. target position of 30° would be between 27-33°).

Statistical Analysis

Statistical analysis was done using SPSS version 25 (IBM SPSS Statistics, Chicago, IL). two, three-way repeated measures analyses of variance (ANOVA) were used to examine the effects of condition (passive vs. active with trolley vs. active without trolley) and position (30° vs. 45° vs. 60° of flexion) on the dependent variables of constant and absolute errors. Significant difference was accepted at an α level of 0.05. Simple effects analyses were conducted in the event of a significant condition by position interaction effect. Partial eta squared (η_p^2) was used to indicate effect sizes, with benchmarks of 0.2, 0.5, and 0.8 used to denote small, medium, and large effects, respectively (Cohen, 1988).

In the case of a non-significant interaction, but significant main effects of either condition or position, pairwise comparisons were conducted, with a Bonferroni correction.

Results

Constant Error

Mauchly's test indicated that the CE data did not violate the assumption of sphericity for the condition by position interaction (p = .448), nor for the main effects of condition (p = .17) or position (p = .727). Therefore, no correction to the degrees of freedom were made when evaluating the results of the two-way ANOVA. The two-way ANOVA revealed no significant condition by position interaction effect on constant error (CE) (F[4, 60] = .798, p = .531, $\eta_p^2 =$ .049). There was also no significant main effect of position on CE (F[2, 30] = .619, p = .545, $\eta_p^2 = 0.04$). However, CE was significantly affected by condition, with a medium effect size (F[2, 30] = 9.94, p = .001, $\eta_p^2 = 0.394$). A linear contrast showed decreasing CE with decreased levels of active muscle control of movement and positioning across positions (passive on trolley < active on trolley < active without trolley) (p = .001) (Figure 2).

Absolute Error

As with CE, mauchly's test indicated that the AE data did not violate the assumption of sphericity for the condition by position interaction (p = .558), nor for the main effects of condition (p = .09) or position (p = .892). Therefore, no correction to the degrees of freedom were made when evaluating the results of the two-way ANOVA.As observed for CE, the two-way ANOVA revealed no significant condition by position interaction effect on absolute error (AE) (F[4, 60] = 1.10, p = .367 η_p^2 = 0.065). There was also no significant main effect of position on AE (F[2, 30] = 3.05, p = .062, $\eta_p^2 =$ .169). However, AE was significantly affected by condition, with a medium effect size(F[2, 30] = 4.18, p = .025, $\eta_p^2 = 0.211$). As with CE, a linear contrast showed decreasing AE with decreased levels of active muscle control of movement and positioning across positions (passive on trolley < active on trolley < active without trolley) ($p = .024$) (Figure 3).

Discussion

The current study investigated the effects of the degree of hip control (passive, supported movement vs. active, supported movement vs. active, unsupported movement) and hip position (30° vs. 45° vs. 60° hip flexion) on JPS acuity (AE and CE) in healthy subjects. It was hypothesized that an active unconstrained assessment would have a reduction of repositioning error than constrained JPS assessment. The results of the study revealed a linear decrease in both absolute and constant error scores as the degree of active muscle support decreased. This did not support the original hypothesis that active JPS would be more accurate and decrease error score values compared to passive.

The subjects in the current study accomplished joint repositioning tasks in an unconstrained model. A subject required to support their own limb weight can often be intrinsically a part of an unconstrained model task (Benjaminse et al., 2009). Limb support, or weight bearing has been previously investigated by comparison of applying external force to the subject and results indicated that adding weight to the limb positively influenced joint position acuity levels (Suprak et al., 2007). There is limited research that have shown passive joint position sense in healthy populations produced greater accuracy than active (Ju, Weng & Cheng, 2010; Laufer et al., 2001). For the hip joint, the current study results may have revealed that stabilization simply takes priority over being accurate during flexion (Giphart et al., 2012; Retchford et al., 2013). Stabilization in the hip has been well established in research (Diamond et al., 2017; Retchford et al., 2013), and joint position sense has contribution to control of hip muscles (Torry et al., 2006). Thus, active JPS trials would have required more sense of effort towards stabilization rather than consciously focusing on the target position.

Results from previous studies indicate that if active joint repositioning is more accurate than passive, it is due to increased muscle activation from the requirement of the subject to support their own limb (Benjaminse et al., 2009; Pickard et al., 2003). Benjaminse and colleagues (2009) suggested that the need to maintain balance during testing became the sole focus from the subject rather than the repositioning task, causing an increase in active JPS error scores. Previous studies have documented that muscle activation influences joint proprioceptive acuity (Suprak et al., 2016). In the current study, the condition of active JPS without hip trolley may have required subjects to activate hip abductors (TFL and gluteus medius/maximus) and external rotators (hip rotator cuff muscles and gluteus maximus) along with hip flexors (iliopsoas and rectus femoris) (Retchford et al., 2013). The increased muscular demand may have caused activation of abdominal muscles to increase lumbar fascia stiffness (Hodges & Richardson, 1997; Kopeinig et al., 2015). Increased stiffness in the lumbar region, in aims to stabilize, could also have caused anterior pelvic tilt (Neumann, 2010). Thus, pelvic tilt and stiffness of lumbar fascia and musculature could have affected perception of the target position and increasing error scores.

Previous findings from Pickard and colleagues (2003) were contrasted with the current study. They found that active joint repositioning was more accurate than passive whereas the current study findings showed that passive reproduction was more accurate than active reproduction (Pickard et al., 2003). However, the subjects in the current study were laying on their sides rather than in the previous study, during which subjects lay supine (Pickard et al., 2003). Orientation of the body influences the groups of muscles activated during the active conditions compared to passive conditions during movement. When laying supine, primary muscles involved in hip flexion are the same as laying on the side. However, lying supine would require abdominal and lumbar muscles to stabilize the hip during motion compared to subject laying on their side and stabilize with external rotators (Neumann, 2010).

The current study comes with some limitations. Subjects' hip ROM was not determined prior to JPS testing. It has previously been stated that ROM of a joint can influence JPS acuity (Jami, 1992). If the positions that were chosen (30, 45, 60 of flexion) were towards a subjects' end range of motion, specific mechanoreceptors (e.g. Ruffini endings, skin receptors) would be most sensitive (Collins et al., 2005; Macefield, 2005; Proske & Gandevia, 2012). As a result, a decrease of error scores would occur. In contrast, if a subjects' ROM was large (surpassing 60 of flexion), other mechanoreceptors (e.g. muscle spindles, GTOs) are most sensitive within the midrange of motion (Janwantankul et al., 2001; Suprak et al., 2005; Proske & Gandevia, 2012). In addition, musculotendinous receptors like GTOs have increased sensitivity when a muscle activation occurs (Jami, 1992; Macefield, 2005). This could be a considerable influence seen by the reduction of error scores the more supported and less involved the limb perceived.

Even though the current study did not result with active conditions to have decrease in error scores, future studies should continue to investigate hip JPS because of its application to functional movements (e.g. walking, squatting, etc.). Breathing and changes in intra-abdominal pressure has been exhibited to increase low back muscles and fascia stiffness (Hodges & Richardson, 1997; Hodges et al., 2005). Low back pain and joint position sense have been tested previously (Li et al., 2008). However, intra-abdominal pressure changes and fascia stiffness should be investigated further in its effects on hip proprioceptive abilities or investigation of breathing technique effects on lumbopelvic proprioception.

Conclusions

The current study revealed that there was a continuous decrease in error scores as the testing apparatus became more supportive the tested limb. Limiting gravitational effects by an external support (hip trolley) could have elicited a response of increase sensitivity of capsuloligamentous mechanoreceptors. Future research should consider that proprioceptive sensitivity can be dependent on muscular activity.

References

1. Adamo, D.E., 2007. Age-related differences in upper limb proprioceptive acuity. Percept. Mot. Skills 104, 1297.
2. Allen, T.J., Proske, U., 2006. Effect of muscle fatigue on the sense of limb position and movement. Exp. Brain Res. 170, 30–38.
3. Alzaharani, A., Bali, K., Gudena, R., Railton, P., Ponjevic, D., Matyas, J.R., Powell, J.N., 2014. The innervation of the human acetabular labrum and hip joint: an anatomic study. BMC Musculoskelet Disord 15, 41.
4. Amiri-Khorasani, M., Osman, N.A.A., Yusof, A., 2011. Acute effect of static and dynamic stretching on hip dynamic range of motion during instep kicking in professional soccer players. J. Strength Cond. Res. 25, 1647–1652.
5. Arvin, M., Hoozemans, M.J., Burger, B.J., Verschueren, S.M., van Dieën, J.H., Pijnappels, M., 2015. Reproducibility of a knee and hip proprioception test in healthy older adults. Aging Clin. Exper. Res. 27, 171–177.
6. Benjaminse, A., Sell, T.C., Abt, J.P., House, A.J., Lephart, S.M., 2009. Reliability and precision of hip proprioception methods in healthy individuals. Clin. J. Sport. Med. 19, 457–463.
7. Bardakos, N.V., Villar, R.N., 2009. The ligamentum teres of the adult hip. Bone Joint J. 91, 8–15.
8. Birnbaum, K., Prescher, A., Heþler, S., 1997. The sensory innervation of the hip joint - An anatomical study. Surg. Radiol. Anat. 19, 371–375.
9. Blum, K.P., Lamotte D'Incamps, B., Zytnicki, D., Ting, L.H., 2017. Force encoding in muscle spindles during stretch of passive muscle. PLOS Comp. Bio. 13, e1005767.

10. Bressel, E., Yonker, J.C., Kras, J., Heath, E.M., 2007. Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. J. Athl. Train. 42, 42.

11. Bridgeman, B., 2007. Efference copy and its limitations. Comp. Bio. Med. 37, 924–929.

12. Cohen, J. ,1988. Statistical power analysis for the behavioral sciences (2nd ed.)Erlbaum, Hillsdale, NJ:.

13. Collins, D.F., 2005. Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee. J. Neurophysio. 94, 1699–1706.

14. D'Lima, D.D., Leardini, A., Witte, E.H., Chung, S.G., Christofolini, L., Wu, G., 2000. Standard for hip joint coordinate system recommendations from the international society of biomechanics comittee.

15. Daneshjoo, A., Mokhtar, A.H., Rahnama, N., Yusof, A., 2012. The effects of comprehensive warm-up programs on proprioception, static and dynamic balance on male soccer players. PLoS ONE 7, e51568.

16. Dehao, B.W., Bing, T.K., Young, J.L.S., 2015. Understanding the ligamentum teres of the hip: a histological study. Acta Ortopédica. Brasileira 23, 29–33.

17. Desteli, E.E., Gülman, A.B., Imren, Y., Kaymaz, F., 2014. Comparison of mechanoreceptor quantities in hip joints of developmental dysplasia of the hip patients with normal hips. HIP Intern. 24, 44–48.

18. Diracoglu, D., Aydin, R., Baskent, A., Celik, A., 2005. Effects of kinesthesia and balance exercises in knee osteoarthritis. J. Clin. Rheumatol. 11, 303–310.

19. Dover, G., Powers, M.E., 2003. Reliability of joint position sense and force-reproduction measures during internal and external rotation of the shoulder. J. Athl. Train. 38, 304.

20. DiZio, P., Lacknet, J.R., 2002. Proprioceptive adaptation and aftereffects, in: Hale, K.S, Stanney, K.M. (Ed.), Handbook of Virtual Environments. CRC Press Boca Raton, FL, pp.791–812.
21. Durbaba, R., Taylor, A., Ellaway, P.H., Rawlinson, S., 2001. Modulation of primary afferent discharge by dynamic and static gamma motor axons in cat muscle spindles in relation to the intrafusal fibre types activated. J. Physiol. 532, 563–574.
22. Durbaba, R., Taylor, A., Ellaway, P.H., Rawlinson, S., 2003. The influence of bag 2 and chain intrafusal muscle fibres on secondary spindle afferents in the cat. J. Physiol. 550, 263–278.
23. Edwards, S. E., Lin, Y.-L., H. King, J., R. Karduna, A., 2016. Joint position sense – There's an app for that. J. Biomech. 49, 3529–3533.
24. Elangovan, N., Herrmann, A., Konczak, J., 2014. Assessing proprioceptive function: Evaluating joint position matching methods against psychophysical thresholds. Phys. Therap. 94, 553–561.
25. Erickson, R.I.C., Karduna, A.R., 2012. Three-dimensional repositioning tasks show differences in joint position sense between active and passive shoulder motion. J. Orthop. Res. 30, 787–792.
26. Evangelos, B., Georgios, K., Konstantinos, A., Gissis, I., Papadopoulos, C., Aristomenis, S., 2012. Proprioception and balance training can improve amateur soccer players' technical skills. J. Phys. Ed. Sport. 12, 81.
27. Fitzpatrick, R., McCloskey, D.I., 1994. Proprioceptive, visual and vestibular thresholds for perception of sway during standing in humans. J. Physiol. 1, 173–186.

28. Friemert, B., Bach, C., Schwarz, W., Gerngross, H., Schmidt, R., 2006. Benefits of active motion for joint position sense. Knee Surg. Sports Traumatol. Arthr. 14, 564–570.
29. Gandevia, S.C., 1996. Kinesthesia: roles for afferent signals and motor commands, in: Handbook of Physiology, Exercise: Regulation and Integration of Multiple Systems. 128–172.
30. Gandevia, S.C., 1999. Mind, muscles and motoneurones. J. Sci. Med. Sport 2, 167–180.
31. Gerhardt, M., Johnson, K., Atkinson, R., Snow, B., Shaw, C., Brown, A., Vangsness, C.T., 2012. Characterisation and classification of the neural anatomy in the human hip joint. HIP Intern. 22, 75–81.
32. Giphart, J.E., Stull, J.D., LaPrade, R.F., Wahoff, M.S., Philippon, M.J., 2012. Recruitment and activity of the pectineus and piriformis muscles during hip rehabilitation exercises: An electromyography study. Am. J. Sports Med. 40, 1654–1663.
33. Goble, D.J., 2010. Proprioceptive acuity assessment via joint position matching: from basic science to general practice. Phys. Ther. 90, 1176–1184.
34. Gregory, J.E., Brockett, C.L., Morgan, D.L., Whitehead, N.P., Proske, U., 2002. Effect of eccentric muscle contractions on Golgi tendon organ responses to passive and active tension in the cat. J. Phys. 538, 209–218.
35. Han, J., Waddington, G., Adams, R., Anson, J., Liu, Y., 2016. Assessing proprioception: A critical review of methods. J. Sport. Health. Sci. 5, 80–90.
36. Haversath, M., Hanke, J., Landgraeber, S., Herten, M., Zilkens, C., Krauspe, R., Jäger, M., 2013. The distribution of nociceptive innervation in the painful hip: A histological investigation. Bone Joint J. 95-B, 770–776.

37. Homan, K.J., Norcross, M.F., Goerger, B.M., Prentice, W.E., Blackburn, J.T., 2013. The influence of hip strength on gluteal activity and lower extremity kinematics. J. Electromyogr. Kines. 23, 411–415.

38. Hospod, V., Aimonetti, J.-M., Roll, J.-P., Ribot-Ciscar, E., 2007. Changes in Human Muscle Spindle Sensitivity during a Proprioceptive Attention Task. J. Neurosci. 27, 5172–5178.

39. Hung, Y. -j., Darling, W.G., 2012. Shoulder Position Sense During Passive Matching and Active Positioning Tasks in Individuals With Anterior Shoulder Instability. Phys. Therap. 92, 563–573.

40. Hurley, M.V., Rees, J., Newham, D.J., 1998. Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle-aged and elderly subjects. Age Ageing 27, 55–62.

41. Ishii, Y., Tojo, T., Terajima, K., Terashima, S., Bechtold, J.E., 1999. Intracapsular components do not change hip proprioception. J. Bone Joint Surg. Am. 81, 345–348.

42. Jaffar, A.A., Abass, S.J., Ismael, M.Q., 2006. Biomechanical aspects of shoulder and hip articulations: a comparison of two ball and socket joints. Al-Khwarizmi Engineer J 2, 1–14.

43. Jami, L., 1992. Golgi tendon organs in mammalian skeletal muscle: functional properties and central actions. Physiol. Rev. 72, 623-666.

44. Janwantanakul, P., Magarey, M.E., Jones, M.A., Dansie, B.R., 2001. Variation in shoulder position sense at mid and extreme range of motion. Arch. Phys. Med. Rehabil. 82, 840–844.

45. Ju, Y.Y., Wang, C.W., Cheng, H.Y.K., 2010. Effects of active fatiguing movement versus passive repetitive movement on knee proprioception. Clin. Biomech. 25, 708–712.

46. Kabbaligere, R., Lee, B.-C., Layne, C.S., 2017. Balancing sensory inputs: Sensory reweighting of ankle proprioception and vision during a bipedal posture task. Gait Posture 52, 244–250.

47. Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., 1990. Measurement of lower extremity kinematics during level walking. J. Orthrop. Res. 8, 383–392.

48. Kapetanakis, S., Dermon, A., Gkantsinikoudis, N., Kommata, V., Soukakos, P., Dermon, C., 2017. Acetabular labrum of hip joint in osteoarthritis: A qualitative original study and short review of the literature. J. Orthop. Surg. 25, 230949901773444.

49. Kaplan, F.S., Nixon, J.E., Reitz, M., Rindfleish, L., Tucker, J., 1985. Age-related changes in proprioception and sensation of joint position. Acta Orthop. Scand. 56, 72–74.

50. Keogh, M.J., Batt, M.E., 2008. A Review of Femoroacetabular Impingement in Athletes. Sports Med. 38, 863–878.

51. Kerbel, Y.E., Smith, C.M., Prodromo, J.P., Nzeogu, M.I., Mulcahey, M.K., 2018. Epidemiology of hip and groin injuries in collegiate athletes in the united states. Orthop. J. Sports Med. 6, 232596711877167.

52. Kilicarslan, K., Kilicarslan, A., Demirkale, I., Aytekin, M.N., Aksekili, M.A.E., Ugurlu, M., 2015. Immunohistochemical analysis of mechanoreceptors in transverse acetabular ligament and labrum: A prospective analysis of 35 cases. Acta Orthop. Traumatol. Turc. 49, 394–398.

53. Kim, Y.T., Azuma, H., 1995. The Nerve Endings of the Acetabular Labrum: Clin. Orthop. Related Res. 320, 176-181.

54. Kopeinig, C., Gödl-Purrer, B., Salchinger, B., 2015. Fascia as a proprioceptive organ and its role in chronic pain - A review of current literature. Saf. Health Work. 1, A2.
55. Kumar, V.P., Balasubramaniam, P., 1985. The role of atmospheric pressure in stabilising the shoulder: an experimental study. Brit. Editor Society Bone Joint Surg. 67-B, 719–721.
56. Kwon, O., Lee, S., Lee, Y., Seo, D., Jung, S., Choi, W., 2013. The effect of repetitive passive and active movements on proprioception ability in forearm supination. J. Phys. Ther. Sci. 25, 587–590.
57. Laufer, Y., Hocherman, S., Dickstein, R., 2001. Accuracy of reproducing hand position when using active compared with passive movement. Physiother. Res. Int. 6, 65–75.
58. Leardini, A., Cappozzo, A., Catani, F., Toksvig-Larsen, S., Petitto, A., Sforza, V., Cassanelli, G., Giannini, S., 1999. Validation of a functional method for the estimation of hip joint centre location. J. Biomech 32, 99–103.
59. Lephart, S.M., Pincivero, D.M., Giraido, J.L., Fu, F.H., 1997. The role of proprioception in the management and rehabilitation of athletic injuries. Am. J. Sports Med. 25, 130–137.
60. Leunig, M., Beck, M., Stauffer, E., Hertel, R., Ganz, R., 2000. Free nerve endings in the ligamentum capitis femoris. Acta Orthop. Scand. 71, 452–454.
61. Lewis, C.L., Sahrmann, S.A., Moran, D.W., 2007. Anterior hip joint force increases with hip extension, decreased gluteal force, or decreased iliopsoas force. J. Biomech. 40, 3725–3731
62. Li, L., Lamis, F., Wilson, S.E., 2008. Whole-body vibration alters proprioception in the trunk. Int. J. Ind. Ergon. 38, 792–800.

63. Lin, C.-H., Lien, Y.-H., Wang, S.-F., Tsauo, J.-Y., 2006. Hip and knee proprioception in elite, amateur, and novice tennis players. Am. J. Phys. Med. Rehabil. 85, 216–221.

64. Lin, D.-H., Lin, C.-H.J., Lin, Y.-F., Jan, M.-H., 2009. Efficacy of 2 non-weight-bearing interventions, proprioception training versus strength training, for patients with knee osteoarthritis: a clinical trial. J. Orthop. Sports Phys. Therap. 39, 450–457. https://doi.org/10.2519/jospt.2009.2923

65. Macefield, V.G., 2005. Physiological characteristics of low-threshold mechanoreceptors in joints, muscle and skin in human subjects. Clin. Exp. Pharmacol. Physiol. 32, 135–144.

66. Magill R., Anderson D., 2014. Motor learning and control: concepts and application. McGraw-Hill Publishing, New York, NY.

67. Mason, J.B., 2001. Acetabular labral tears in the athlete. Clin. Sports Med. 20, 779–789.

68. Michelson, J.D., Hutchins, C., 1995. Mechanoreceptors in human ankle ligaments. J. Bone Joint Surg. 77, 219–224.

69. Moraes, M.R., Cavalcante, M.L., Leite, J.A., Macedo, J.N., Sampaio, M.L., Jamacaru, V.F., Santana, M.G., 2011. The characteristics of the mechanoreceptors of the hip with arthrosis. J. Orthop. Surg. Res. 6, 58.

70. Muaidi, Q.I., Nicholson, L.L., Refshauge, K.M., 2008. Do elite athletes exhibit enhanced proprioceptive acuity, range and strength of knee rotation compared with non-athletes?: Enhanced proprioceptive acuity, range and strength of knee rotation. Scan. J. Med. Sci. Sports 19, 103–112.

71. Nagai, T., Sell, T.C., House, A.J., Abt, J.P., Lephart, S.M., 2013. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. J. Ath. Train. 48, 31–38.
72. Neumann, D.A., 2010. Kinesiology of the hip: A focus on muscular actions. J. Orthop. Sports Phys. Therap. 40, 84–94.
73. O'Donnell, J.M., Devitt, B.M., Arora, M., 2018. The role of the ligamentum teres in the adult hip: redundant or relevant? A review. J. Hip Preserv. Surg. 5, 15–22.
74. Onishi, H., Nagoya, S., Takebayashi, T., Yamashita, T., 2017. Analysis of proprioception of hip joint in total hip arthroplasty. Open J. Orthop. 07, 53–62.
75. Pickard, C.M., Sullivan, P.E., Allison, G.T., Singer, K.P., 2003. Is there a difference in hip joint position sense between young and older groups? J. Gerontol. A-Biol. 58, M631–M635.
76. Powers, C.M., 2010. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J. Orth. Sports Phys. Ther. 40, 42–51.
77. Prather, H., Colorado, B., Hunt, D., 2014. Managing hip pain in the athlete. Phys. Med. Rehabil. Clin. N. Am. 25, 789–812.
78. Proske, U., Gandevia, S.C., 2009. The kinaesthetic senses: The kinaesthetic senses. J. Physiol. 587, 4139–4146.
79. Proske, U., Gandevia, S.C., 2012. The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force. Physiol. Rev. 92, 1651–1697.
80. Proske, U., 2005. What is the role of muscle receptors in proprioception? Muscle Nerve 31, 780–787.

81. Retchford, T.H., Crossley, K.M., Grimaldi, A., Kemp, J.L., Cowan, S.M., 2013. Can local muscles augment stability in the hip? A narrative literature review. J. Musculoskelet. Neuronal. Interact. 13, 1–12.
82. Riemann, B.L., Lephart, S.M., 2002. The sensorimotor system, part II: the role of proprioception in motor control and functional joint stability. J. Ath. Train. 37, 80.
83. Riemann, B.L., Lephart, S.M., 2002. The sensorimotor system, part I: the physiologic basis of functional joint stability. J. Ath. Train. 37, 71.
84. Rogol, I.M., Ernst, G., Perrin, D.H., 1998. Open and closed kinetic chain exercises improve shoulder joint reposition sense equally in healthy subjects. J. Ath. Train. 33, 315.
85. Röijezon, U., Clark, N.C., Treleaven, J., 2015. Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions. Man. Therap. 20, 368–377.
86. Sarban, S., Baba, F., Kocabey, Y., Cengiz, M., Isikan, U.E., 2007. Free nerve endings and morphological features of the ligamentum capitis femoris in developmental dysplasia of the hip. J. Ped. Orthop. B 16, 351–356.
87. Schuenke, M., Schulte, E., Schumacher, U., 2014. Atlas of anatomy: general anatomy and musculoskeletal system. Thieme. New York, NY.
88. Sherrington, C.S., 1907. On the proprioceptive system, especially in its reflex aspect. Brain, 29, 467-482.
89. Smirmaul, B. de P.C., 2012. Sense of effort and other unpleasant sensations during exercise: clarifying concepts and mechanisms. Brit. J. Sports Med. 46, 308–311.

90. Stillman, B.C., McMeeken, J.M., Macdonell, R.A., 1998. Aftereffects of resisted muscle contractions on the accuracy of joint position sense in elite male athletes. Arch. Phys. Med. Rehab. 79, 1250–1254.

91. Suprak, D.N., Dawes, J., Stephenson, M.D., 2011. The effect of position on the percentage of body mass supported during traditional and modified push-up variants. J. Strength Cond. Res. 25, 497–503.

92. Suprak, D.N., Osternig, L.R., van Donkelaar, P., Karduna, A.R., 2006. Shoulder joint position sense improves with elevation angle in a novel, unconstrained task. J. Orthop. Res. 24, 559–568.

93. Suprak, D.N., Osternig, L.R., van Donkelaar, P., Karduna, A.R., 2007. Shoulder joint position sense improves with external load. J. Moto. Behav. 39, 517–525.

94. Suprak, D.N., Sahlberg, J.D., Chalmers, G.R., Cunningham, W., 2016. Shoulder elevation affects joint position sense and muscle activation differently in upright and supine body orientations. Hum. Mov. Sci. 46, 148–158.

95. Swinnen, E., Baeyens, J.-P., Pintens, S., Van Nieuwenhoven, J., Ilsbroukx, S., Buyl, R., Ron, C., Goossens, M., Meeusen, R., Kerckhofs, E., 2014. Trunk kinematics during walking in persons with multiple sclerosis: the influence of body weight support. Neuro. Rehab. 34, 731–740.

96. Torry, M.R., Schenker, M.L., Martin, H.D., Hogoboom, D., Philippon, M.J., 2006. Neuromuscular hip biomechanics and pathology in the athlete. Clin Sports Med 25, 179–197.

97. Voight, M.L., Hardin, J.A., Blackburn, T.A., Tippett, S., Canner, G.C., 1996. The effects of muscle fatigue on and the relationship of arm dominance to shoulder proprioception. J. Orthop. Sports Phys. Ther. 23, 348–352.
98. Walsh, L.D., Hesse, C.W., Morgan, D.L., Proske, U., 2004. Human forearm position sense after fatigue of elbow flexor muscles. J. Phys. 2, 588.
99. Wingert, J.R., Welder, C., Foo, P., 2014. Age-related hip proprioception declines: effects on postural sway and dynamic balance. Arch. Phys. Med. Rehab. 95, 253–261.
100. Wingstrand, H., Wingstrand, A., Krantz, P., 1990. Intracapsular and atmospheric pressure in the dynamics and stability of the hip. A biomechanical study. Acta. Orthop. Scand. 61, 231-235.
101. Winter, J.A., Allen, T.J., Proske, U., 2005. Muscle spindle signals combine with the sense of effort to indicate limb position: Muscle spindles, effort and position sense. J. Physiol. 568, 1035–1046.
102. Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D D'Lima, D., Cristofolini, L., Witte, H., 2002. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. J. Biomech. 35, 543–548.

Tables

TABLE 1. SUBJECT DEMOGRAPHICS	MEAN (SD)
AGE, Y	22 (1.72)
HEIGHT, CM	169.04 (10.45)
MASS, KG	69.54 (8.46)
EXERCISE FREQUENCY (DAYS/WK)	3.78 (1.24)

Figures

Fig 1. A) frontal view of subject testing apparatus with hip trolley B) Posterior view of testing apparatus.

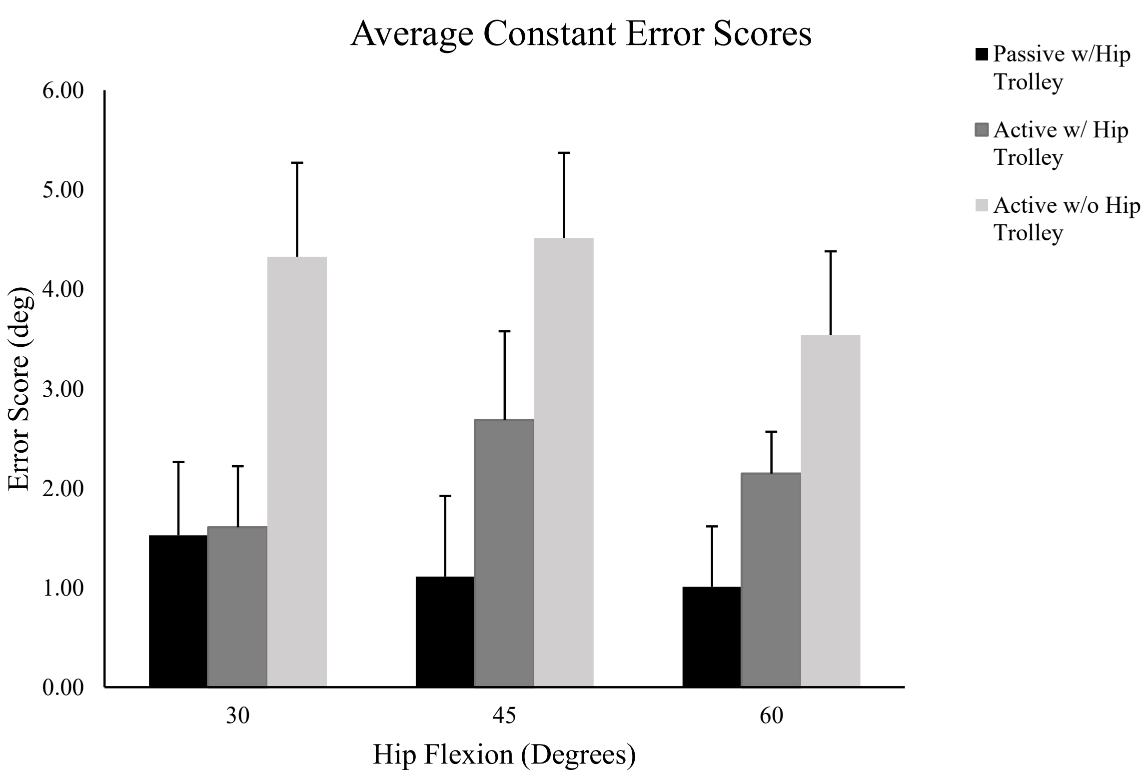

Figure 2. Average (SD) Constant Error Score Values.

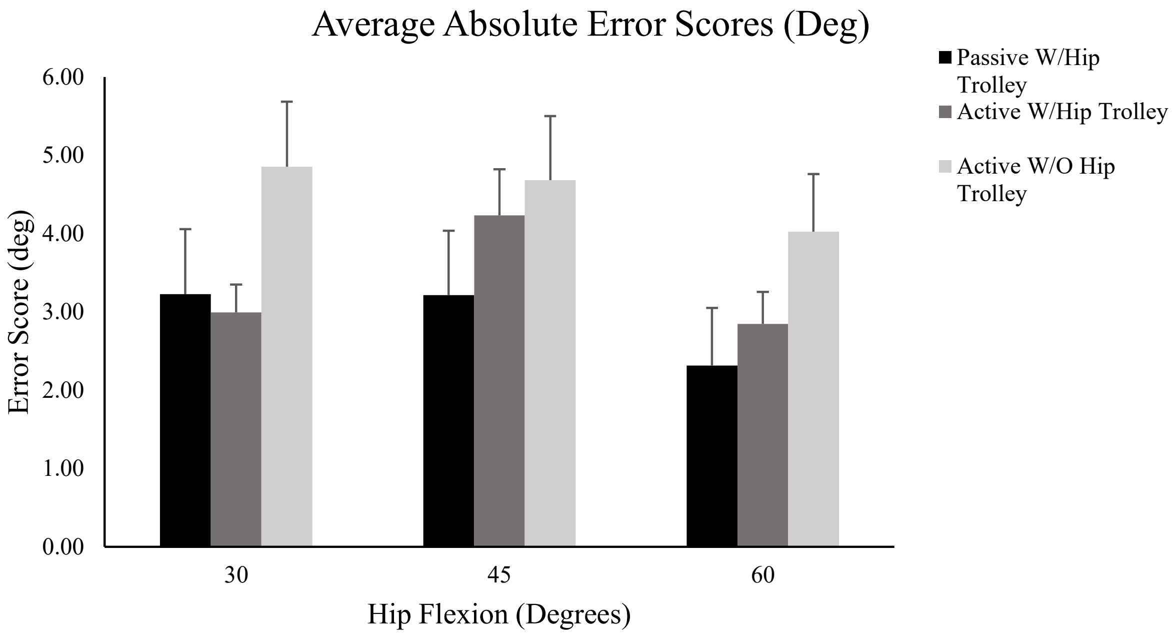

Figure 3. Average (SD) Absolute Error Score Values.

Appendix A

Journal Guide for Authors

Aims and scope

Affiliated with the American Society of Biomechanics, the International Society of Biomechanics, the European Society of Biomechanics, the Japanese Society for Clinical Biomechanics and Related Research and the Australian and New Zealand Society of Biomechanics.

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5. ***Book Reviews,*** normally no longer than 1000 words (by invitation from the Book Review Editor only).
6. ***Letters to the Editor*** normally no longer than 1000 words.

Note: All of the above word limit is for the manuscript text alone and does not include the abstract, references, equations, tables, figure captions or appendices.

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3. A separate title page should include the title, authors' names and affiliations, and a complete address for the corresponding author including telephone and fax numbers as well as an E-mail address. Authors should supply up to five keywords. Keywords may be modified or added by the Editors. Please provide a word count (Introduction through Discussion) on the title page. All pages, starting with the title page, should be numbered.

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The *Journal of Biomechanics* supports the ARRIVE (Animal Research: Reporting In Vivo Experiments) guidelines to improve standards of reporting of animal experiments and ensure that the data can be fully evaluated and utilized [http://www.nc3rs.org.uk/page.asp?id=1357] (Kilkenny C, Browne WJ, Cuthill IC, Emerson M, Altman DG (2010) Improving Bioscience Research Reporting: The ARRIVE Guidelines for Reporting Animal Research. PLoS Biol 8(6): e1000412. doi:10.1371/journal.pbio.1000412). Adherence to these recommendations will greatly facilitate the review of manuscripts, decrease the likelihood of multiple revisions, and improve the chances of acceptance for publication.

6. Acknowledgements should be included after the end of the Discussion and just prior to the References. Include external sources of support.

7. The text should be ready for setting in type and should be **carefully checked for errors** prior to submission. Scripts should be typed double-spaced.

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C. Theses
van Werff, K., 1977. Kinematic and dynamic analysis of mechanisms. A finite element approach. PhD. thesis, Delft University Press, Delft.

D. Proceedings
van Soest, A. J., van den Bogert, A. J., 1991. Criteria for the comparison of direct dynamics software systems to be used in the field of biomechanics. In Proceedings of the 3rd International Symposium on Computer Simulation in Biomechanics. University of Western Australia, Perth.

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Appendix B

WWU IRB Notification

WESTERN WASHINGTON UNIVERSITY

INSTITUTIONAL REVIEW BOARD

APPROVAL FOR USE OF HUMAN SUBJECTS

TYPE OF REQUEST:	☒ new	☐ modification

PROTOCOL NUMBER:	19-030
PROJECT TITLE:	Healthy Hip Joint Position Sense
INVESTIGATOR:	Julianna Johnson
FACULTY ADVISOR:	Dave Suprak
DEPARTMENT:	Psychology
DETERMINATION:	**Approved**
DATE:	6/12/2019
CATEGORY:	Expedited Category 4
CONDITIONS:	NA

Approved by: ____________________ Date: 6/12/19
Institutional Review Board

Comments:

IRB approval must be obtained in advanced before making any changes to your research. Applications should be closed when all interaction or intervention with human subjects or their identifiable data is complete. Instructions on how to modify or close an application are available on our website: <u>www.wwu.edu/compliance</u>. Please report any noncompliance, unanticipated problems, or complaints related to your research.

Appendix B

Application Approval Signatures

Principal Investigator Agreement

I have read and agree to uphold with the responsibilities of the Principal Investigator as outlined on page 3 of this application. I attest that the materials provided in support of this application are an accurate reflection of the proposed research.

Julianna Johnson

Principal Investigator Name

5/28/19

JJ

Principal Investigator Signature

Date

Faculty Advisor Agreement

I have read and approve the attached application submitted for review. I agree to provide appropriate education and supervision of the student investigator and share the Principal Investigator responsibilities as stated above.

David N. Suprak

Faculty Advisor Name

5/28/19

David N. Suprak

Faculty Advisor Signature

Date

Department Chair Agreement

I certify that I have reviewed this research protocol and that I attest:

- to the competency of the investigator(s) to conduct the research;
- that facility, equipment, and personnel are adequate to conduct the research; and
- that continued guidance will be provided to the investigator as appropriate.

Keith Russell

Department Chair Name

K. C. Russell

5·29·2019

Appendix B

Application: Human Subjects Research

IRB Use Only Protocol #: 19-030	RECEIVED JUN 06 2019 RSP	APPROVED BY HSRC 6/12/19 DATE	
Review Status: ☐ Exempt ☒ Expedited ☐ Full Cat: 4		Approval Period: NA to NA	
Reviewer 1: [signature]	Date: 6/6/19		
Reviewer 2: MJ Mosher	Date: 6/11/19	Notes:	

1. Investigator Information

Principal Investigator (PI) *(One per application is allowed)*			
First Name:	**Julianna**	Last Name:	**Johnson**
Degrees:	**BS**	Department:	**HHD**
Home Institution:	**WWU**	Address/Mail stop:	**8622 27th AVE SE**
Phone:	**360-584-3720**	Email:	**johns888@wwu.edu**
Status:	☐ Faculty ☐ Staff	☒ Graduate student	☐ Undergraduate Student

Faculty Advisor *(Required when Undergraduate & Graduate Students are listed as PIs)*			
First Name:	**David**	Last Name:	**Suprak**
Home Institution:	**WWU**	Department:	**HHD**
Position:	**Associate Professor**	Address/Mail stop:	
Phone:		Email:	**dave.suprak@wwu.edu**

PI Proxy *(A researcher authorized for correspondence with the IRB, if different from the Principal Investigator)*					
First Name:		Position:		Phone:	
Last Name:		Address/Mail stop:		Email:	

2. Study Information

2.1 Short Study Title: Healthy Hip JPS

Appendix C

Data

Average of Trial Absolute Error (Deg)	Column Labels														
	1			1 Total	2			2 Total	3			3 Total	(blank	(bla	Grand Total
Row	**1**	**2**	**3**		**1**	**2**	**3**		**1**	**2**	**3**		**(blank)**		
10	3.3838	1.9828	0.7516	**2.0394**	2.7750	1.7803	3.2500	**2.6018**	3.1395	3.3257	3.6222	**3.3624**			2.6679
11	4.1669	2.5981	0.8216	**2.5289**	1.8333	1.8964	2.7616	**2.1638**	6.3881	4.8953	5.5488	**5.6107**			3.4345
12	2.3331	0.9741	1.0071	**1.4381**	1.6873	8.7954	4.0092	**4.8306**	1.4670	4.1103	2.8425	**2.8066**			3.0251
13	1.8876	3.4609	2.5491	**2.6325**	1.7438	5.4309	0.9491	**2.7079**	2.9511	4.3503	1.5261	**2.9425**			2.7610
14	3.5783	3.5616	2.7735	**3.3045**	3.6852	2.1186	0.7471	**2.1836**	2.1589	3.7316	1.1397	**2.3434**			2.6105
15	4.1986	2.4166	0.6390	**2.4180**	5.9077	8.9801	3.5551	**6.1476**	5.4549	6.2296	4.9573	**5.5473**			4.7043
16	2.0921	4.3149	2.8185	**3.0752**	0.5113	3.5367	0.9525	**1.6668**	4.2700	3.3019	3.5499	**3.7073**			2.8164
18	3.8062	4.2612	4.0950	**4.0541**	2.0566	5.9433	6.7251	**4.9083**	9.2610	7.6968	9.4403	**8.7994**			5.9206
19	1.4826	4.0145	4.3888	**3.2953**	1.8945	4.7662	4.5011	**3.7206**	4.4931	5.8605	7.2797	**5.8778**			4.2979
20	3.0037	4.0541	2.2470	**3.1016**	3.7839	5.5713	2.4280	**3.9277**	0.8419	1.3991	3.2701	**1.8370**			2.9554
21	2.0989	1.6339	3.2133	**2.3154**	4.4573	0.9597	0.7294	**2.0488**	5.1358	1.4439	0.4938	**2.3578**			2.2407
22	1.3467	1.6187	0.8516	**1.2723**	2.5224	2.5156	1.1711	**2.0697**	3.7584	2.0438	0.9238	**2.0524**			1.7884
23	3.7305	2.7011	5.2881	**3.9066**	4.7265	4.4449	2.9717	**4.0477**	6.9784	4.2407	10.2345	**7.5150**			5.0657
24	4.2495	2.9839	1.9015	**3.0450**	2.4831	4.4536	3.4216	**3.4528**	14.3464	14.9920	4.9202	**11.4195**			5.9724
25	6.6240	9.0612	2.6455	**6.1102**	3.4472	3.9780	3.5584	**3.6612**	4.6056	5.4228	3.5872	**4.5386**			4.7700
26	3.6713	1.8380	1.0352	**2.1815**	4.3830	2.5866	3.8055	**3.5917**	2.4597	1.8714	1.0608	**1.7973**			2.5235
(blank)															
Grand Tot	**3.2284**	**3.2172**	**2.3141**	**2.9199**	**2.9936**	**4.2349**	**2.8460**	**3.3582**	**4.8802**	**4.6916**	**4.0248**	**4.5286**			**3.5979**

Appendix C

Average of Trial Constant Error (Deg)	Column Labels 1			1 Total	2			2 Total	3			3 Total	(bl	(blan	Grand Total
Row Labels	1	2	3		1	2	3		1	2	3		(blank)		
10	3.3838	1.9227	0.1704	**1.8257**	-0.1124	-0.2261	3.2500	**0.9705**	-0.1753	3.3257	3.6222	**2.2575**			1.6846
11	4.1669	2.5981	0.8216	**2.5289**	0.6068	1.8964	2.7616	**1.7549**	6.3881	4.8876	5.5488	**5.6082**			3.2973
12	2.1582	-0.0545	-0.3994	**0.5681**	-1.6873	8.7954	2.4537	**3.1873**	-1.0184	4.1103	1.1612	**1.4177**			1.7244
13	-1.2315	-3.4609	-2.5491	**-2.4139**	-1.7438	-3.8319	0.9491	**-1.5422**	2.9128	4.3503	1.2183	**2.8271**			-0.3763
14	1.7223	-1.0772	-1.2984	**-0.2178**	3.3783	2.1186	0.7471	**2.0813**	1.6629	3.7316	0.5457	**1.9801**			1.2812
15	4.1986	0.9025	0.0442	**1.7151**	5.9077	8.9801	3.5551	**6.1476**	5.4549	6.2296	4.9573	**5.5473**			4.4700
16	-2.0921	-4.3149	-2.8185	**-3.0752**	0.0112	-0.9411	0.4144	**-0.1718**	4.2700	3.3019	3.5499	**3.7073**			0.1534
18	3.8062	4.2612	4.0950	**4.0541**	2.0566	3.8276	-1.8251	**1.3530**	9.2610	7.6968	9.4403	**8.7994**			4.7355
19	0.7597	4.0145	4.3888	**3.0543**	1.8945	4.7662	4.5011	**3.7206**	2.5307	5.8605	7.2797	**5.2236**			3.9995
20	-0.0066	1.3828	2.2188	**1.1983**	2.6925	5.5713	2.4280	**3.5639**	0.8419	1.3991	-0.3291	**0.6373**			1.7999
21	-2.0989	0.9478	3.2133	**0.6874**	4.4573	0.9597	0.7294	**2.0488**	5.1358	1.4439	-0.3094	**2.0901**			1.6088
22	-0.9985	-1.6187	0.2928	**-0.7748**	-2.5224	-2.5156	0.6002	**-1.4793**	3.7584	1.2357	0.3121	**1.5200**			-0.3126
23	3.7305	-1.2940	5.2881	**2.5749**	4.7265	3.2728	2.9717	**3.6570**	6.9784	3.7556	10.2345	**7.3937**			4.4322
24	3.9636	2.6899	0.9284	**2.5273**	1.4777	4.4536	3.4216	**3.1176**	14.3464	14.9920	4.9202	**11.4195**			5.6881
25	6.6240	9.0612	2.5868	**6.0907**	3.4472	3.9780	3.5584	**3.6612**	4.4029	5.4228	3.5872	**4.4710**			4.7409
26	-3.6713	1.8380	-0.8288	**-0.8874**	1.1038	1.8119	3.8055	**2.2404**	2.4597	0.4992	0.9414	**1.3001**			0.8844
(blank)															
Grand Total	**1.5259**	**1.1124**	**1.0096**	**1.2160**	**1.6059**	**2.6823**	**2.1451**	**2.1444**	**4.3377**	**4.5313**	**3.5425**	**4.1330**			**2.4902**