บทความวิชาการ

How do knee joint and its alignment contribute to the postural control of quiet stance?

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Abstract

The control of human quiet stance has long been the subject of interest for decades. Biomechanical and neurological studies have been extensively evaluated to create the understanding of how human control their stance stability. Even though many studies have committed that human stance is much similar to the single inverted pendulum (SIP), recent studies revealed the multi-joint coordination to be more efficiently control strategy. The studies of multi-joint coordination are growing in number these days, and this may indicate the importance to study the role of other joints, i.e., the knee joint, in contributing to balance control during quiet standing. Despite aiding in control balance, the exact role of the knee joint has never been reported, further investigations are needed. Since the ankle and hip joints are linked at the knee joint, thus the alignment of the knee joint may affect the postural strategies elicited during balance correction. Researchers found that individuals with knee hyperextension, mal-alignment between femur and tibia, demonstrated poorer stance stability, but they were still be able to respond to external perturbations resemble to normal knee alignment individuals. Some researchers speculated that individuals with hyper-mobility of the knee joint may have impaired proprioception of the knee near end range from flexion to extension. When the proprioception is altered, the postural control system might also be altered since the proprioception is important for planning and adjusting body position and movement. In spite of the same postural responses, the question of how the central nervous system (CNS) controls those movements remains.

Keywords: Quiet stance, Postural control, Knee hyperextension, Inverted pendulum

บทคัดย่อ

การศึกษาที่เกี่ยวข้องกับการควบคุมการทรงท่าขณะยืนนิ่งได้รับความสนใจมาเป็นเวลานาน นักวิจัยได้ทำการศึกษาทั้งด้านชีวกลศาสตร์และระบบประสาทที่ทำหน้าที่ควบคุมการเคลื่อนไหวเพื่อหาคำตอบว่ามนุษย์ควบคุมการทรงท่านี้ได้อย่างไร นักวิจัยในช่วงเริ่มต้นทำการศึกษามีความเห็นตรงกันว่าการทรงท่าของมนุษย์ขณะยืนนิ่งมีลักษณะคล้ายทรงกรวยคว่ำ (inverted pendulum) อย่างไรก็ตาม งานวิจัยในปัจจุบันแสดงให้เห็นว่าร่างกายมีการทำงานประสานสัมพันธ์ระหว่างข้อต่อต่างๆทั่วร่างกายเพื่อให้ร่างกายอยู่ในสมดุลการทรงท่าที่ดี ซึ่งแนวคิดนี้เป็นที่ยอมรับเพิ่มมากขึ้นเรื่อยๆและยังแสดงให้เห็นถึงความสำคัญของข้อต่ออื่นๆรวมถึงข้อเข่าว่ามีผลต่อการทรงท่าขณะยืนนิ่งด้วย งานวิจัยในระยะต่อมาพบว่าข้อเข่ามีส่วนช่วยในการทรงท่าแต่ยังไม่มีการรายงานบทบาทที่ชัดเจน ทำให้ยังคงต้องทำการศึกษาบทบาทของข้อเข่าต่อความสามารถในการควบคุมการทรงท่า ข้อเข่าเป็นข้อต่อที่เชื่อมต่อทั้งข้อเท้าและข้อสะโพกการเปลี่ยนแปลงใดๆที่ข้อเข่าจึงอาจส่งผลต่อข้อต่อทั้งสองและอาจส่งผลต่อการตอบสนองของ postural strategy การจัดเรียงตัวของกระดูก (alignment) เป็นปัจจัยหนึ่งซึ่งมีผลต่อการทรงท่า นักวิจัยพบว่ากลุ่มตัวอย่างอาสาสมัครที่มีข้อเข่า

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แอ่นมีความสามารถในการทรงท่าขณะยืนนิ่งน้อยกว่ากลุ่มอาสาสมัครที่มีข้อเข่าปกติ แต่ความสามารถในการปรับตัวต่อการรบกวนการทรงท่าได้ไม่แตกต่างกัน จึงยังไม่ชัดเจนว่าลักษณะการควบคุมการเคลื่อนไหวของประชากรทั้งสองกลุ่มจะเหมือนหรือแตกต่างกันนักวิจัยบางกลุ่มได้ตั้งข้อสังเกตว่าประชากรที่มีช่วงการเคลื่อนไหวของข้อเข่ามากกว่าปกติอาจมีความสามารถในการรับรู้ตำแหน่งและการเคลื่อนไหว (proprioception) ของข้อเข่าผิดปกติไป ซึ่งเมื่อไม่สามารถรับรู้ตำแหน่งหรือการเคลื่อนไหวของข้อต่อได้อย่างถูกต้อง จึงอาจส่งผลให้มีความสามารถในการทรงท่าลดลงเนื่องจากความสามารถในการรับรู้ตำแหน่งของข้อต่อนี้มีความสำคัญต่อการวางแผนการเคลื่อนไหวและปรับท่าทางของร่างกาย แม้ว่าประชากรที่มีข้อเข่าแอ่นสามารถปรับการทรงท่าได้ไม่แตกต่างจากประชากรที่มีข้อเข่าปกติ แต่ยังไม่มีงานวิจัยใดสามารถอธิบายความแตกต่างในด้านการควบคุมจากระบบประสาทระหว่างอาสาสมัครทั้งสองกลุ่ม

Introduction

Quiet stance is one of the most common tasks used in our daily activities. It is characterized as having a small amount of spontaneous postural sway, both anteroposterior (AP) and mediolateral directions[1]. It has been the subject of the biomechanics and motor control researches for decades, but the clear explanation of the quiet stance has yet to be clarified. Earlier studies show that the quiet stance is mainly controlled and organized through the musculature and passive stiffness of the ankle joint. This is known as the single inverted pendulum (SIP) model[2]. However, recent studies have shown that the single inverted pendulum is an over-simplified model and that all three joints of the lower extremity are involved in the control of the stance stability[3, 4]. This means that the knee joint also plays role.

The body alignment can affect the stance stability since it allows the body to efficiently spend the muscular effort to be maintained in equilibrium[1]. However, the alignment of the joint of the body can vary among people. Considering the alignment of the knee joint, its variation in the sagittal plane usually puts the joint in the hyperextended position. In this case, the line of gravity is shifted far forward from the ideal position[5]and changes the load distribution of the articular surface. This may cause the injuries to the articular bones and the ligaments of the knee joint which the joint mechanoreceptors are pervaded[6]. Injury to the joint mechanoreceptors may disrupt the proprioceptive function of the knee joint and cause adverse consequences to the postural control system[6].

The researchers reported that the knee hyperextension affected the stance stability as shown by the higher center of pressure (CoP) velocity[7]. The explanation was not clear why and how the knee hyperextension caused the different postural sway since the evidence that examined the effect of knee hyperextension on postural control in healthy individual was scarce. The key answer to this question may lie within the proprioceptive capability of these individuals which is now still conflicting.

Even though the hyperextended knee individuals demonstrated poorer stance stability, the postural adjustments about the knee joint were comparable to the normal knee alignment individuals[7]. The questions remained whether the neuromuscular control between the normal and hyperextended knee participants would be the same. The aims of this review were to explore the role of knee joint and its neuromuscular control in postural control and whether there was a difference in postural control between the normal knee alignment and hyperextended knee individuals. The information presented in this review consisted of the biomechanical models of the quiet stance. The postural control of quiet stance which provided the basic information about the sensory and motor systems that involved in the control of quiet stance were also recruited. Importantly, the contribution of the sensory information, especially the proprioception, was included into this review since the literature pointed out the important role of the sensory information on feedback control mechanism of the human postural response[1].

Biomechanical models of the quiet stance

The biomechanical models have been developed to explore the processes of central nervous system (CNS) in the control of quiet stance. Identifying the movements related to the postural task like quiet stance may help the reader to understand the nature of quiet stance.

The inverted pendulum

The inverted pendulum model has been developed to investigate how the CNS controls human upright standing position[2]. The outcome of the control element, particularly the kinetics of human movements, is reported as the integrated results of movement control namely center of pressure (CoP). The inverted pendulum model predicts that the difference between CoP and CoM (CoP-CoM) is proportional to the horizontal acceleration of the CoM, assuming that the moving body above the ankle joint moves as a rigid structure. The difference between the CoP and CoM acts as an error signal that the control system uses to regulate the movements of the whole body. The position of the CoP under each foot expresses the neural control of the ankle muscles[2]. For example, when the CoM is shifted forward during forward sway, the CNS senses that change and causes the individual to increase their CoP by generating the plantar flexor torques to counteract the sway and return the body position to its earlier steady position[2]. Hence, the CoP related parameters are frequently used in the research to compare the stance stability of the individuals, as well as to discriminate people at risk of fall[2, 8].

The earlier assumption implied that the human quiet stance was similar to the SIP model which had been validated by Winter and colleagues[2] and re-validated by Gage and colleagues[3]. The study by Gage and colleagues confirmed the idea that human body swayed as an inverted pendulum by tracking the movements of infrared emitting diode (IRED) markers placed along the longitudinal axis of the body during standing. They found that the angular displacement of each IRED marker linearly increased as the height of the marker increased. Furthermore, the relationship between body segment CoM displacement and whole body CoM displacement was also well correlated[3].The movements of the markers resembled the shape of the inverted pendulum with fulcrum at the ankle joint which supported the concept of the inverted pendulum. However, new evidences did not fully support the idea of SIP[3, 4, 9].

De Freitas and colleagues re-examined the concept of the SIP by constraining knees, hips and trunk simulating the rigid body above the ankle joint. The results showed an increased in postural sway and so did the COP velocity. This means that the movement regulation at the ankle joint alone might be insufficient to control the balance during standing[9].

Creath and co-workers demonstrated that the double inverted pendulum (DIP) was concurrently presented with the SIP even during quiet stance[10]. The DIP was the synergistic movements of the ankle and the hip joints in order to correct postural deviation. It was primarily thought to be invoked only when the postural control system was perturbed[1]. Creath and co-workers classified the movement patterns between the leg and trunk segments into in-phase and anti-phase patterns according to the power spectral density of movement frequency. The in-phase, considered as the leg and trunk segments moved in the same direction, was found at the frequency below 1 Hz. On the other hand, the anti-phase was found at the frequency above 1 Hz and was considered as the legs and trunk segments moved in the opposite directions. The in-phase could be compared to the SIP while the anti-phase could be compared to the DIP. They thought that the presence of these two mechanical movements of the body were selected strategies by the CNS. They suggested that further investigations were needed to explore how the CNS selected and coordinated these movements[10].

The updated evidences pointed out that the SIP was an oversimplified model[4, 9-11]. The more advanced technology combined with the movement analysis techniques allow the researchers to extend the model of quiet stance more comprehensively. Actually, some kinematics studies had shown some contribution of joints other than the ankle joint during quiet stance[3, 4, 7].

Multijoint coordination: the more explicative model

The study by Hsu and co-workers revealed small angular movements at joints along the longitudinal axis of the body and showed that human stance was inherently unstable[4]. Using the three dimensional study, they found that joints along the longitudinal axis of the body were destabilised and re-stabilised at all time to regain a stable position. These joints included the ankle, knee, hip, lumbo-sacral junction, C7-T1 junction and atlanto-occipital joint. A small amount of the knee joint angular displacement even during quiet stance was also found. Giving that joint angles varied, the body CoM position was quite relatively stable[4].

In accordance with Hsu's study, Gage and coworkers speculated the displacement of the IRED markers of the knee joints even during normal stance on a fixed supporting surface. Gage reported that the displacement of the ankle joint markers were lower than that of the other joint markers, including the knee joint markers. The researchers also reported that the relationship between the knee joint angular displacement and the whole body CoM displacement was higher than that of the ankle angular displacement and the whole body CoM displacement. Gage proposed that the movement of the knee joint allowed the lower extremities to track the body CoM more consistently than when only the ankle movement alone was considered[3].

The study by Gunther and co-workers further supported the contribution of the knee joint during quiet standing[11]. Integrating the knee joint into the model also resulting in the more effective control of stance stability. The knee joint showed coupling movement as well as torque coupling to both the ankle and hip joints. Considering the joint movements, the ankle and knee joints showed strong angular coupling both in-phase and anti-phase correlation. The knee and hip joint angular coupling also presented but less than ankle-knee angular coupling. The joint torque between the ankle and knee joints were highly correlated in all trials, but knee joint torque and hip joint torque was less strong but still considered as high correlation. They suggested that the knee joint offered more dynamic mechanical control of the quiet stance[11].

The data from the literature were less likely to corporate the knee joint into the model of the control of quiet stance. The main joints that were thought to be responsible for postural strategy seem to involve only the ankle and the hip joints. This speculation led to a question whether the knee joint was pre-programmed to be rigidly moved during postural adjustment[12]. To answer this question, Di Giulio and co-workers conducted a study to evaluate the role of the knee joint in postural control of quiet stance. Using gentle knee joint perturbation (applied pulling force 1 - 10 N), their results demonstrated two patterns of responses with ones, great number of the participants, kept their knees straight while the others let their knees flexed and moved in accordance with the perturbation[12]. Their findings represented two different postural strategies, keeping the knee straight and flexing the knee.

Why the majority of the participants kept their knee straight? The reasons for keeping their knees straight might be explained through the geometry of the articular surface and the biomechanics of the knee joint in full extension position. When the knee is placed in full extension, the screw home mechanism puts the knee joint in a close pack position that ensures the most stability position of the joint. By all means, this joint position creates a stable position and generates more proprioceptive information at once[6, 13]. Although the knees were kept straight during perturbations, other alternative strategies could not be disregarded as some participants had their knees flexed. Flexing the knee joints during standing might be another strategy that human used to lower the body COM in order to increase stability which offered some benefits to the postural control system. The study by Pereira and colleagues demonstrated the greater stability measured with Biodex Stability System when participants stood with their knees slightly flexed rather than kept the knees straight[14].

The multijoint coordination contradicts the assumption of the SIP model. The CNS makes special efforts to limit sway of the body by coordinating movements at all joints such that most joint motion is decoupled from motion of the body in space[4]. To coordinate movements of the joints across the body requires a good postural control.

Postural control of quiet stance

The control of quiet stance is truly dynamic processes that need a good coordination between the neural and musculoskeletal systems. The nervous system controls body equilibrium and reacts in response to sensory feedbacks to achieve a stable upright position. The interaction between the perception system and action system is essential to keep balance[1]. An active sensory processing along with the constant mapping of perception to action is needed, so that the postural control system is able to detect body position in space and can anticipate which direction the body is moving to. To know exactly where the body is in space, the CNS needs sensory information from the visual, vestibular, and somatosensory systems. These three sensory systems form the perceptual system which provides the brain with important and unique information regarding the ability of each system[1].

The visual system provides the sense of head position and movement in space, as well as the sense of verticality. Moreover, it also provides information about the relationship between the body and environment. The vestibular system aids in detection of the head positions and movements with respect to gravity and inertial forces. Lastly, the somatosensory system provides the central nervous system with the positions and movements of the body regarding support surface. In addition, somatosensory inputs from various sources of the body aid in determining relationship among body segments[1]. In order to gain maximal stability, all three sensory systems are required otherwise body sway increases[1, 15]. It was reported that the individuals with somatosensory or vestibular loss were able to stand quietly as normal individuals, given that one out of the three sensory was well preserved[15]. However, these individuals showed a difficulty in selecting an appropriate postural strategy when they were imposed to some kind of environmental constraint. The availability of the three sensory systems, hence allowed the individuals to coordinate movements and to select as well as to execute appropriate postural strategies[15]. Among the three sensations, the proprioception is the most influential sensation to the control of quiet stance.

The proprioception

Proprioception is the capability of the individual to perceive body positions and movements in space, and is based on the sensory signals deriving from the muscle spindle, joint mechanoreceptors, and the cutaneous receptors without the use of visual information[16-19]. Some researchers suggested that the motor cortex may contribute in detecting joint movements[20]. The proprioceptive afferents reach the brain via the posterior column-dorsal lemniscal pathway[19]. These signals synapse at many levels within the CNS and are integrated to create the perception of the extremities and trunk positions, thereto execute accurate movements and to avoid an extreme joint range of motion preventing joint injury. The roles of the proprioception can be categorised into two aspects as being described below.

The role of proprioception in postural control

The role of proprioception in postural control is extremely vital. The sensory from both internal and external cues help individuals to adapt motor performance to match the task being performed and surrounded environment. The proprioceptive information is used to plan and modify motor outputs[21]. The signals project to areas of the cerebral hemisphere. These areas include primary somatosensory areas (area 2 and 3a), primary motor cortex, premotor cortex, supplementary motor cortex, cingulate motor area, and cerebellum[20, 22]. These cortical areas work together to plan and initiate movements to achieve smooth and coordinated movements. The supplementary motor area is responsible for initiating and controlling internally generated movements, while the premotor area is responsible for controlling the movements that are activated by external stimuli. As the motor commands from the primary motor cortex project to the muscles, the cerebellum compares the motor output with the goal movement. The motor control undergoes constant review and modification based upon the integration and analysis of sensory inputs, efferent motor commands, and resultant movements. If the movement does not achieve the goal, the CNS adjusts them. This process is instantaneous, ongoing process which helps us achieve smooth and well-coordinated movements[1].

The other aspect of the proprioception aiding the postural control is concerning the external environment. The example of this situation is when individuals use the proprioceptive cues to adjust their body position to external perturbation, such as walking on uneven surface. They can sense the roughness of the supporting surface and adjusting the ankle position before they see it. Moreover, the responses to proprioceptive cues, in this situation, are faster and more accurate than those to the visual information[21].

The role of proprioception and functional joint stability

Underlying the execution of all motor tasks are particular events that are aimed at preparing, maintaining, and restoring stability of both the entire body (postural stability) and the body segments (joint stability). The joint and muscle stiffness together with viscoelasticity of the ligaments allow individuals to safely move their joint through range of motion. The attachments of the ligament guide the movement of the adjoining bones[21]. Both muscle and ligament exhibit neural properties that accomplish each other in stabilising joint from unexpected perturbations via ligamento-muscular reflex[6, 21]. The neural signals from the stretched ligaments trigger muscular response related to the function of these ligaments. The knee joint stability is formed by the mechanical properties of muscles, tendons, ligaments, and joint capsules along with the neural properties from the stretched ligaments surrounding it[6]. The anterior cruciate ligament (ACL), as one of the main ligament of the knee joint, is also found involved in the activation of hamstring muscle reflex. The synergistic activation of the hamstrings muscle prevents excessive anterior tibial translation[6]. The interactions between sensory inputs and motor outputs represent neuromuscular control which contributes to joint stability. The translation from sensory signals to motor outputs is managed by the action system.

The action system of the postural control

The action systems are fundamental to motor control and movements[1]. These systems include the areas of the frontal cortex, brain stem, cerebellum, spinal networks, motor neurone, and muscles. The main factors that have influences on the control of quiet stance include postural tone, muscle tone, and body alignment. The postural tone refers to muscle activity that is generated by postural muscles during upright position, while the muscle tone refers to muscle activity that increases due to the muscle is being elongated. Body alignment could affect how our body reacts to the gravitational force[1]. The joint alignment varies among people, some are normal but some may be considered as abnormal. Knee hyperextension is one of the most common joint variations seen in the community that may lead to the destruction of knee joint structures and is more likely to develop degenerative joint disease[5, 23].

Knee hyperextension: Biomechanical and Structural alterations

Knee hyperextension is characterised as having range of knee extension beyond anatomical position. The range of motion more than 5 degrees extension is considered as having knee hyperextension[5], another characterisation defines the knee hyperextension to be as much as 10 degrees beyond anatomical position[24].

The complexity of the knee joint geometry allows the joint to be moved in 6 degrees of freedom combining gliding and rolling through all movements[13]. When the knee is moved from flexion to extension, the femur rolls anteriorly and glides posteriorly on the fixed tibia. During terminal extension, the femur continues to internally rotate over the tibia. If the knee is hyperextended, the femur does not continue to roll anteriorly but tilts forward instead. This movement causes the anterior compression between the femur and tibia[5]. Fish and Kosta identified types of knee hyperextension into three distinct profiles according to rotary alignment of the tibia: knee hyperextension with external rotary deformity, knee hyperextension with internal rotary deformity, and knee hyperextension without tibial rotation[13]. When deviation occurs, it can alter the alignment of the joints proximally and distally at a time. Shultz and colleagues found the association between knee hyperextension and anterior knee joint laxity[25]. The presence of greater knee hyperextension simultaneously with foot pronation was the strongest predictors of anterior knee joint laxity[25]. The ankle-foot complex and weight distribution might also be disturbed.

The causes of knee hyperextension are various. It may be inherited or acquired through training, i.e., ballet dancer or gymnast. Considering the cause of knee hyperextension from the knee joint structures, it can be classified into three types, knee hyperextension with alterations of bony elements, knee hyperextension with stretching of soft tissue elements, and knee hyperextension with bony and soft tissue alterations (mixed type)[26]. These alterations cause the alignment of the bones to deviate from the normal anatomical position. The changes of the knee alignment interrupt the soft tissues around and within the knee joint.

The common soft tissues that are usually interrupted in the knee hyperextension mostly found at the posterolateral corner of the knee joint. These structures include the ACL, lateral collateral ligament (LCL), tendon of popliteus muscle, and lateral head of gastrocnemius muscle[5, 27]. Among these structures, the ACL is frequently involved in hyperextension injury of the knee joint. The mechanoreceptors that signal proprioceptive information to the CNS can also be found in the ACL[6]. Consequently, the ACL has influence upon knee joint stability via mechanical and neuromuscular functions. Its mechanical properties help prevent excessive anterior tibial translation and knee extension. The neurological property of the ACL is capable of restriction of the motion of knee extension through activation of the hamstring muscle reflex (Di Fabio et al., 1992). Once it is injured, the movement as well as the neuromuscular control of the knee joint is altered[6, 25, 28].

From the data described above, the knee hyperextension causes the deviation of the knee joint itself[5] as well as the hip joint and the ankle-foot complex[13]. This information may reflect the altered weight acceptance and weight distribution within the foot during standing and walking. Moreover, the neurological properties of the ligament that aid postural control system are also disrupted[6, 28]. The biomechanical alteration accompanies with the altered sensory perception, though not obviously, can lead to a poor postural control.

Knee hyperextension affects postural control

Siqueira and colleagues conducted a study to investigate whether knee hyperextension affected human stance stability[7]. Their results revealed that when postural control was more challenged, most of the participants tended to bend their knees as they tried to regain postural stability. The difference of COP velocity was found between normal knee and knee hyperextension groups. During standing on firm surface with eye open, the knee hyperextension group showed higher COP velocity in the AP direction. However, in the most challenging condition, i.e., standing on foam surface with eyes closed, the knee hyperextension group showed the lowest COP velocity[7]. The COP velocity is used to describe the postural control ability[8]. Thus, it may be concluded that the ability to control stance stability of individuals with knee hyperextension might be differ from those individuals with normal knee alignment. The results from Siqueira's study were in accordance with the concept of the effects of body alignment on postural control of quiet stance. Even the same postural responses were found in Siqueira's study, we still lack the neuromuscular control information.

A person who exhibits knee hyperextension may have impaired proprioception of the knee joint near end range of knee flexion to extension[5]. This is still questionable whether the ability to detect knee position of individuals with knee hyperextension is preserved. The pilot study of Loudon and colleagues found that individuals with knee hyperextension were unable to reproduce knee joint angle in the last 15 degrees of extension[5]. However, the study by Stillman et al. was on the contrary. They reported that the individuals with knee hyperextension were able to reproduce knee joint angle within 15 degrees from their knee extension limit with more accurate and reliable than normal participants[24]. The ability of individuals with knee hyperextension in detecting knee joint position sense is still controversial.

Conclusion

Biomechanical studies of postural control supported the role of knee joint in postural control during quiet stance. The contribution of the knee joint may aid the body to track the movement of whole body COM more consistently. Once the alignment of the knee joint is changed, the ability to keep the body equilibrium is also changed. In individuals with knee hyperextension, the CNS is still able to regulate and respond to postural disturbance. Although the similar response pattern has been observed, how the CNS control and respond to the perturbation is unknown. Additionally, the ability to detect knee joint position in these people is controversial. Further investigation is needed to explore how knee joint contribute in control of quiet stance.

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