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Task-Dependent Postural Control Throughout The Lifespan

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Abstract

Routine activities performed while standing and walking require the ability to appropriately and continuously modulate postural movements as a function of a concurrent task. Changes in task-dependent postural control contribute to the emergence, maturation, and decline of complex motor skills and stability throughout the lifespan.

Keywords

Postural Control; Stability; Lifespan Development; Multi-task behavior; Mobility; Load Handling; Adaptive Locomotion

INTRODUCTION

When performing many daily activities, individuals must adopt body configurations, orientations, and movements that allow upright stance to be maintained while other tasks such as walking, talking, and manipulating objects are performed (15, 32). Our main hypothesis is that the ability to adapt posture as a function of a concurrent goal-directed task

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is a critical component of daily life. This task-dependent control of posture largely contributes to the development, maintenance, and decline of complex motor skills and stability throughout the lifespan (8, 18, 19). Using linear and non-linear analytical techniques, we found that infants exhibit rudimentary task-dependent postural control concurrent with the onset of independent stance (8). Specifically, they control posture to facilitate performance of a manual task. Improvements in task-dependent postural control throughout childhood likely contribute to the ability of young adults to control and adjust posture in a complex manner when performing seemingly routine activities, such as when performing a precision manual task (15), a visual fixation task (4), or while handling a load (18, 35). With age, a decline in the ability to properly control posture based on the demands of a concurrent goal-directed task likely contributes to an increased risk of falling (29). In this review, we discuss the integration of posture with other goal-directed behaviors, emphasizing lifespan changes in task-dependent postural control.

INTEGRATION OF POSTURE WITH OTHER GOAL-DIRECTED BEHAVIORS

Bipedal stance is inherently unstable. Humans have a small base of support coupled with a high center of mass, which increases the likelihood of a fall. Typically, this instability is examined during quiet stance using various sensory manipulations and/or perturbations, e.g. (20, 28). Although these studies have provided valuable information regarding the mechanisms governing postural control, it is unclear how the quiet standing paradigm relates to daily life, as people rarely stand for the sake of standing. Rather, people more typically stand in order to accomplish a goal-directed task. To successfully perform a task while standing, body position and movement must afford both upright stance and the completion of the concurrent goal-directed task. The control of posture while performing a concurrent task has previously been conceptualized using configuration space diagrams (31). While these diagrams can represent a wide range of goal-directed behaviors, we will focus on a concurrent manual task (Figure 1).

When performing the manual task depicted in Figure 1, the body can adopt any orientation within the white region. If body orientations move into the gray region, the manual task cannot be successfully completed but upright stance is still maintained. If body orientations pass beyond the gray region, the individual will either lose balance or need to take a step. The morphology of the configuration plots are determined by the constraints that emerge from the interaction between the task, individual, and environment. Task constraints predominately influence the boundaries of the white region. As demonstrated in Figure 1, the white region is smaller and translated towards the stability boundary (boundary separating the gray and black regions) when performing the precision task. Less body sway can be tolerated since postural movements could reduce manual accuracy or cause balance to be compromised. Additionally, the white and gray regions can change as a function of individual constraints such as disease, and frailty. For example, frail individuals would have smaller white and gray regions, increasing the likelihood that postural movements could hinder performance and/or stability.

A number of important points can be derived from these configuration space diagrams. First, for most activities, posture must be controlled in a manner that affords both upright stance and the completion of a task. In some circumstances, the individual may choose to accept reduced performance of the goal-directed task so that they can remain upright (such as minimizing body lean when performing a precision task beyond arm's length). Second, when viewing postural control within a task-dependent framework, it is difficult to categorize the magnitude of postural sway as "good" or "bad." Postural movements do not present a threat to task performance or balance as long as they remain within the white region. Increased postural sway is only detrimental when the white region is small and close

to the unstable (black) region (31). As discussed below, in some instances postural sway may actually benefit task performance. Third, examining the morphology and changes of the configuration space could be helpful in diagnosing motor disorders and testing the efficacy of treatment. This approach explains why motor difficulties often do not manifest unless a challenging posture is adopted, such as leaning to reach beyond arm's length or above the head (29).

THE ROLE OF POSTURAL VARIABILITY

Postural sway (or variability) inevitably emerges from the control of a multi-degree of freedom system. Variability has been traditionally viewed as a non-functional byproduct of a noisy motor system, leading to the concept that minimal sway was indicative of a healthy and stable postural system. Recently, this viewpoint has changed and postural variability is now considered to have many functional consequences.

During a standing goal-directed task (Figure 1), postural movements are observed that do not result in improved stability nor aid in the completion of the task (we have termed these 'task-irrelevant movements'), but the individual remains within the white region of the configuration diagram. These movements may aid in the exploration of the environment and allow the individual to learn the morphology of their stability boundary, determine the possibilities for actions, and add flexibility to the postural system (40). The benefit of postural sway from both an exploratory and flexibility framework is discussed below.

Postural Flexibility

The dynamical systems perspective of motor control, learning, and development largely emerged from the theories proposed by Nicoli Bernstein. Bernstein examined how the body's numerous degrees of freedom were controlled and organized during the production of skilled movements (39). Bernstein found expert blacksmiths exhibited variability in the trajectory of the hammer when striking a nail, but the endpoint (hammer-head on the nail) was consistent. Bernstein speculated that the nervous system allowed movement trajectories to vary while tightly controlling the position of the endpoint. The control of posture is also a form of endpoint control. The center of mass is the endpoint that must be controlled so it remains within the base of support. However, variability can be observed in the individual joint trajectories. When performing a standing task, the body's degrees of freedom are adjusted to maintain posture and allow performance of a concurrent task, as demonstrated in the configuration diagrams (Figure 1). The redundancies in the degrees of freedom ultimately provide movement flexibility (39, 40). Conversely, adopting a stiff posture reduces the functional degrees of freedom, hindering the ability to change joint configurations to optimize task performance, and limiting the ability to attenuate perturbations to balance.

Exploratory Postural Movements

The idea that postural sway can be exploratory has mostly evolved from the ecological approach to perception and action (13). Movements are considered exploratory because they provide sensory information regarding the interaction between the individual and environment (7, 13, 31). Thus, the perceiver is not simply a passive recipient of sensory information, but can actively seek new sensory information by generating postural sway.

The perceptual information generated by exploratory postural movements allows the actor to learn the postural boundaries that afford different behaviors. From this perspective, postural sway is beneficial as long as it does not cause a loss of balance or decreased performance of a concurrent standing task. The knowledge gained may facilitate postural control at some point in the future, perhaps during a postural perturbation. Exploratory postural behavior

may also be beneficial when learning a new task or during different periods of the lifespan when the morphology of the configuration space can undergo large-scale changes.

Exploratory behavior may also be present during adaptive locomotion. In a recent study, we observed young healthy adults step over an obstacle for up to 300 trials (21). The foot clearance of the trail limb (second foot to clear the obstacle) progressively decreased with successive trials which, for most subjects, continued until the obstacle was contacted. Although there are various possible explanations for the gradual adjustment in limb height, such as energy minimization, we speculated that the behavior may also reflect an exploratory strategy to gain sensory information regarding obstacle location. This information could be used to optimize trail limb clearance, as the limb is not visible during obstacle crossing. In summary, exploratory movements can be beneficial in a variety of tasks, including quiet standing, performing a goal-directed task while standing, and perhaps even in adaptive locomotion.

TEMPORAL EVOLUTION OF TASK DEPENDENT POSTURAL CONTROL

While performing common activities, environmental constraints (e.g. surface compliancy) and task constraints (e.g. manual precision demands) are dynamic, such that the configuration space changes over time (15, 33). The static behavior depicted in Figure 1 is therefore a simplified version of the configuration space associated with daily activities. Rather, when performing dynamic tasks, the base of support and forces acting on the body can rapidly change. These changes dynamically alter the morphology of the orientations that afford upright stance and allow completion of a concurrent task.

Consider the typical task of picking up a bag of groceries, carrying it to the countertop, and putting the groceries away (Figure 2). The gray regions (configurations that afford upright stance) and white regions (configurations that allow task completion) change as the task unfolds in time. For example, when picking up the bag, the configurations that afford stance are reduced due to the bending motion and the weight of the bag. The white region is reduced along the hip dimension due to the hip flexion required to pick up the bag. These configurations will continue to change as a function of walking and carrying, stepping up stairs, placing the bag, and putting away the groceries. We argue that the ability to remain within the white region that dynamically changes over time is a hallmark of a healthy postural system.

Exploratory postural movements may be most beneficial when performing dynamic tasks. Exploratory movements can continually probe the environment, to determine possibilities for action, and detect new emergent landscapes as the task evolves. Conversely, lack of exploratory postural movement could lead to a decrement in performance because the emergent landscape is not discovered and decisions on task appropriate movements will be slower, less accurate, or inadequate, resulting in an unstable body orientation.

It should be noted that while exploratory postural movements are often functional, in some situations they can compromise upright stance or task performance. An example is standing on ones toes to reach a high shelf (Figure 2). Exploratory movements during this phase are more likely to result in body configurations that move outside of the white region. We argue that an important aspect of task-dependent postural control and healthy motor function is the ability to appropriately and continuously modulate postural movements; postural control does not depend simply on the ability to constrain postural movements. The inability to modulate sway as a function of task, environmental, or individual constraints will result in poor performance, instability, and falls. Next, we discuss how individuals in different periods of the lifespan adjust postural movements based on task demands.

YOUNG ADULTS

Young healthy adults exhibit fairly complex postural control when performing seemingly simple tasks such as visual fixation (4), manual control (15), or handling a load (18, 35). We examined the modulation of posture while performing a manual fitting task (15). The constraints of a manual fitting task change during the evolution of the movement, requiring posture to be dynamically modulated. Participants picked up a block from a table and put it through a shoulder height opening. The size (precision constraint) and distance of the opening (postural constraint) were manipulated. Postural time-to-contact (TtC), the time the center of pressure (CoP) would take to contact the base of support given its instantaneous position, velocity, and acceleration, was calculated. TtC represents the time available to attenuate a perturbation before loss of balance (16, 38); a shorter TtC reflects less stable posture. TtC is well suited to assess posture during dynamic tasks where body position quickly changes relative to the base of support.

TtC was short during the early portion of the fitting task, and became longer as the block approached the opening and the precision demands of the task increased (Figure 3). Postural stability was therefore modulated as a function of the instantaneous demands of the task. Interestingly, postural modulations were less pronounced when fitting through the large opening, suggesting stability was less constrained when postural movements were less likely to interfere with the task (Figure 3).

Postural symmetry as a function of task

Although upright stance appears to be symmetrical in young healthy populations, dual force plate studies have revealed bilateral differences in the forces and CoP profiles under the left and right foot (2). These asymmetries appear to be functional and an important aspect of task-dependent postural control. We have found that the left and right limbs are used differentially during asymmetrical manipulations (18). Participants held a load in either one hand or distributed across both hands. The complexity of CoP under each foot was measured using Sample Entropy, an analytical technique that quantifies the degree of regularity and complexity in the CoP signal. Sample Entropy captures information regarding how the time series unfolds over time and the complex control processes that contribute to upright stance (30). A stiff, less adaptive posture would result in a more regular (lower entropy) CoP signal. Higher values of sample entropy suggest more degrees of freedom are being used, and reflect a more adaptive and complex postural pattern (8).

During asymmetrical load handling, a more rigid leg posture was observed in the loaded limb and a more flexible posture was observed in the unloaded limb. The change in the unloaded limb was an apparent attempt to compensate for the loss of flexibility in the loaded limb (18). Interestingly, the difference in Sample Entropy between the right and left leg increased as the size of the load increased. Similar asymmetrical shifts between stable and flexible postural dynamics have been found to emerge as a function of stance orientation, demonstrating functional stance asymmetries manifest under a variety of task constraints (41).

Trunk control during adaptive locomotion

We have also observed adaptive postural strategies emerge when individuals carried a load while negotiating an elevated surface (35). Traditionally, walking with minimal trunk motion was considered the most stable, since deviations from vertical would cause gravity to accelerate the trunk away from an upright position. In our study, participants (N=10 males, mean age 25 years) carried no load, an empty box, or a loaded box. The box was carried in front of the abdomen, so view of the feet and ground was obstructed. The gait task was

either unobstructed walking or stepping up onto a 15 cm platform. The empty box condition challenged foot trajectory control due to obstructed vision, while the loaded box condition challenged both foot trajectory control and trunk control (due to the extra mass). As expected, trunk motion decreased when carrying the loaded box in both gait tasks, reflecting tighter trunk control. However, when vision was obstructed due to carrying an empty box, gait speed decreased but trunk pitch motion increased in the stepping task, an apparent strategy to gain more visual information during the approach to the platform. Increased trunk pitch motion was not observed when carrying the empty box over the unobstructed walkway or when carrying the loaded box. Therefore, we observed an apparent trade-off between trunk control and foot trajectory control; in a challenging environment, a small decrease in trunk stability resulted in improved visibility and gait speed was decreased to compensate for decreased stability. However, when trunk stability was compromised by added mass, trunk motion strategies were not adopted to increase visual information. These observations highlight the role of the task and the environment in shaping postural strategies.

In summary, young adults control and dynamically adjust posture in a complex manner when performing seemingly routine standing activities. These activities include precision manual movements (15), load-handling while standing (18, 35), and load handling while stepping up to a new level (35). Interestingly, the complex control was specific to the constraints of the task.

DEVELOPMENT

The importance of posture in the development of goal-directed behaviors has been observed in both healthy and impaired children (3). Without the appropriate level of postural control, behaviors such as reaching and locomotion cannot be performed (1, 22). Reaching in healthy children emerges around 4-months of age. Prior to that time, arm movements are uncoordinated and infants are rarely able to grasp an object. Interestingly, if external postural support is provided, pre-reaching infants generate surprisingly mature reaching movements. After the onset of independent reaching, arm kinematics become more organized and controlled when infants are given external postural support (22). Postural deficiencies have also been linked to movement limitations in children with developmental disorders. For example, the immobile postural behavior common to preterm infants has been linked to coordination problems and improper reaching behavior (10). These studies demonstrate that posture is integral to the emergence of motor milestones such as reaching.

The dominant perspective from most motor development research has been that posture is a static foundation upon which other motor behaviors are built. Thus, the majority of infant research investigating the integration of posture with other goal-directed activities has examined execution of the concurrent task (e.g. reaching) without assessing posture. When posture has been examined, stabilization, rather than the integration of posture with a goal-directed behavior, was emphasized. However, we recently found that infants with only a few weeks of standing experience adapted the dynamics of postural sway when performing a goal-directed task that required them to hold a toy (8). When holding a toy, infants exhibited postural dynamics that were more complex (higher values of Sample Entropy) and a lower magnitude of CoP displacement (measured by a best fit ellipse) as compared to when they did not have a toy. The increased postural complexity suggests infants adopt adaptive postural patterns so that they can stabilize posture to better interact with the toy.

If the postural system of infants is mature enough to demonstrate complex and adaptive behavior, why do infants demonstrate less adaptive movements when not holding a toy? We hypothesize that these apparently immature postural dynamics during quiet standing

represent exploratory postural movements. The lower value of Sample Entropy suggests infants use fewer degrees of freedom for quiet standing, a strategy that would reduce the demands of bipedal stance and facilitate exploratory movements around the base of support. Postural sway with higher amplitude and more regular displacement may demonstrate an important mechanism used by infants when learning how to stand. Thus, similar to younger adults, infants modulate postural dynamics based on the performance of a concurrent task. We argue that research which aims to understand postural control and development should be conducted within a task-dependent framework. When only quiet standing is observed, the postural system looks relatively immature, but this can be misleading.

In adults, we discussed how postural variability sometimes facilitates performance of the goal-directed task. In infants, this is likely not the case since excessive movements interfere with the concurrent task and the ability of the child to remain upright. However, postural variability in infants should not be viewed as non-functional. The infant's main goal may be to learn how to stand and move their body within a dynamically changing environment. Therefore, postural movements, although not conducive to upright stance or the completion of a task, allow infants to experience multiple possibilities for action and to settle upon the most efficient and effective movement patterns for the given environment and task. The production of different movements using varied degrees of freedom enables the infant to learn motor solutions that are effective and actions that are destabilizing. Failures resulting from variable postural movements have been observed across a variety of behaviors and appear to be an important aspect of motor development (25). Although the infant may fall while generating postural movements, it is important to remember infants often fall and do not appear to care when they fall. It appears that nature has engendered infants with the need to keep trying despite multiple failures (25).

Task-dependent postural control throughout childhood

Task-dependent postural control is slowly refined throughout childhood. In a series of studies (14, 17, 19), 7- and 10-year-old children performed a similar fitting task as described earlier. Participants fit a block through either a small or large opening that was placed at either a near (arm's length) or far (1.3 arm's length) distance while standing. When fitting the block through the small opening at a far distance, 7-year-olds exhibited what we termed a 'move and stabilize' strategy. This strategy was characterized by the quick displacement of the trunk (forward lean) in the beginning of the fitting movement. Towards the end of the movement, as the block was about to pass through the opening, the trunk was stabilized and exhibited less movement than what was observed in older children and adults. Older children and adults exhibited a more adaptable strategy, where trunk movements were allowed and used to compensate potential endpoint errors. We termed this more adaptive strategy 'move and modulate' (19). In a subsequent study, we found postural TtC was also modulated during the fitting task in both 7- and 10-year-old children. However, 7-year-olds did not stabilize posture to the same degree as older children and adults during the precision fitting task, demonstrating that the ability to implement task-dependent postural control continues to develop into the second decade of life (17).

Postural dynamics also change throughout childhood. When fitting through the small opening, 10-year-olds and adults exhibit more deterministic CoP patterns (measured using Recurrence Quantification Analysis) compared to 7-year-olds, demonstrating smoother and more predictable patterns (14). This finding was surprising because deterministic CoP patterns have been found to characterize an immature or diseased postural system such as those observed in untrained individuals or individuals with Parkinson's disease (36). The contradictory results likely emerged because past studies utilized a quiet standing paradigm. When performing a fitting task, the smooth and predictable postural movements of adults and 10-year-old children may have allowed the nervous system to better integrate postural

and manual movements so that possible perturbations to the movement can be prospectively attenuated. Thus, a deterministic pattern may facilitate completion of a precision demanding goal-directed task but not be beneficial during quiet standing. Again, we see that the dynamics of stance is task-dependent.

In summary, postural development is critical in the emergence of many motor milestones. Learning how to control posture based on the constraints of a concurrent task is likely a critical and often overlooked aspect of motor development. Complex control of posture emerges early in infancy, but adult-like levels of control develop over a protracted period. Interestingly, across our studies, 10-year-olds often behaved similarly to 7-year-olds when task constraints were difficult (fitting through the small opening at a far distance). However, when the task constraints were easier, 10-year-olds more closely resembled adults. Thus, it appears that difficult tasks may be more useful when examining the time course over which posture becomes integrated with other goal-directed movements.

MIDDLE ADULTHOOD TO SENESCENCE

Falls are a leading cause of injury-related death in older adults (23). Falls often result in long-standing pain, functional impairment, disability, and nursing home admission. Unlike measures such as blood pressure, there are no clinically established norms that relate to postural stability, and it is difficult to assess postural abilities in older adults. We argue that studying postural control as a function of a task and its temporal evolution may be critical for diagnoses and rehabilitation. Adaptive control is a more valid indicator of postural stability than quiet stance. In support of this argument, concurrent performance of a goal-directed task appears to impair balance in everyday life. For example, 62% of falls in older adults occur in the home (29). Many of these falls appear to occur while individuals engage in multi-task activities such as locomotion, carrying objects, and leaning to reach (29).

Postural Control and Multi-Task Behaviors

We examined if the ability to multi-task would be resistant to aging effects if a person's occupation required multi-tasking (34). Roofers work on high, sloped surfaces; they are subject to wind gusts and typically carry heavy loads over cluttered surfaces. The net angular momentum of the head, arms, and trunk (HAT) was examined while carrying loads over an unobstructed walkway and stepping up onto a 15 cm platform for young (mean age 26 years) and middle-aged (mean age 57 years) roofers and controls (all male). Low net HAT momentum reflects greater trunk control and stability. Young roofers and age-matched controls had similar net HAT momentum, suggesting similar postural control. Middle-aged controls had a higher net HAT momentum, demonstrating age-related decrements in postural control when multi-tasking. However, the net HAT momentum of middle-aged roofers was not different from the younger groups. Therefore, roofing experience apparently mitigated the age-related changes in multi-tasking (34).

The above observations are parallel to recent findings that found improvements in dual-tasking were only observed when older adults were trained in the dual-task behavior; single task training did not transfer to dual-task behavior (37). However, this is impractical for therapeutic intervention, because it is not possible to provide training in all standing multi-tasks completed in daily life. Therefore, it is critical to continue to search for interventions that can improve multi-tasking but do not include specific training in each multi-task. We note that the secondary tasks in Silsupadol et al. (37), such as spelling backwards, rely on executive function. However, due to the novel nature of these tasks, learning the task may have occurred during training, leading to the observation that improvement occurred only when participants were trained with the secondary task. Therefore, we argue that

information regarding balance control and adaptability is incomplete without also considering well-practiced and commonly occurring tasks.

Cognition and Communication

Cognitive impairment very likely plays a role in the diminished ability to perform multi-task activities in older adults and adults with neurological impairments such as Parkinson's disease (27). Performing a cognitively demanding task has been shown to influence gait and the control of posture and older adults and adults with Parkinson's disease. The exact mechanism linking cognition to posture and gait is unknown. One dominant hypothesis has been that the motor cognitive task competes for a finite amount of cognitive resources (11). A second hypothesis is that executive functioning limitations contribute to the interference between cognition and action. These limitations are in specific aspects of cognition, such as planning, thinking, initiating, and inhibiting behavior (42). Despite the specific mechanism, it is clear that performing a cognitive task influences the concurrent performance of both gait and posture. Unfortunately, most of the cognitive tasks examined are not common in everyday life, including reciting words backward, reaction time tests, memorization, and mental arithmetic. Although these tasks are well suited to laboratory environments, it is unclear how more real-world cognitively demanding tasks influence postural control.

Communication is a common everyday cognitive task that is often coupled with postural tasks such as walking and standing. Communication is a critical component of daily life and involves language formulation, motor control of the speech system, and comprehension of speech and language produced by an interlocutor. Populations with deficits in executive functioning, such as older adults and people with Parkinson's disease, suffer from subtle changes to language skills. These language defects have been linked to specific areas of executive function, including attention, memory, integration, and inhibition rather than language-specific skill deficits (6). Because language formulation and balance rely on similar areas of executive function, it is likely that individuals with cognitive deficits in these areas would have difficulty performing multi-task activities that involve communication and balance (5).

Examining the interactions between speech production, cognitive-linguistic load, balance, and mobility may elucidate the functional declines in mobility associated with aging. In order to successfully manage tasks involving communication and standing/walking, an individual must allocate cognitive resources to maintain posture, formulate language, and coordinate speech motor control with language. We examined how older adults ($n=9$; mean age = 67; 5 females) managed a standing and speaking task (9). Participants stood and read a passage; the surface was either stable or foam (counterbalanced presentation). While standing on a stable surface, older adults' speech performance was similar to when seated and reading (24). However, when standing on a foam surface, older adults took fewer breaths at major syntactic boundaries and more breaths at locations in the passage that were unrelated to a syntactic boundary. Planning breath pauses is a highly cognitive task, requiring the coordination of speech motor control with language. This planning is important as taking breath pauses at locations unrelated to a syntactic boundary can negatively impact speech naturalness and speech intelligibility because listeners are less able to parse speech into meaningful units. Increasing the difficulty of the balance task, by placing the older adults on a less stable surface, resulted in changes to motor and language coordination for speech, suggesting an interaction between these two tasks at the level of cognitive control.

Interestingly, although communication is a cognitively demanding task that is done in many aspects of daily life, little research has examined how it interferes with the performance of multi-task activities involving balance and mobility. In the context of the configuration space diagrams discussed earlier, we would expect that a communication task would

significantly decrease the gray region in older adults (Figure 4). This decrease would manifest because it would be harder for an older individual to control body configurations close to the limits of upright stability due to increased cognitive demands associated with speech. This reduction in control would increase the chance that the individual would move into the black region and lose balance. The influence of communication and other cognitively demanding tasks on the white region is less clear. It is reasonable to expect that there would be some decrease in the white area. However, this decrease would likely be less than what was observed in the gray area. The change in configuration space morphology could have interesting consequences not previously considered. Specifically, the gray area of the configuration space can be considered a buffer zone. While performing typical daily tasks, if movements go beyond the white region into the gray region, the only consequence is task performance is degraded. However, with age and cognitive decline, this buffer zone is decreased, particularly when engaged in a cognitively demanding task such as communication. The older individual may have an increased risk of falling if they are not aware of their new configuration space morphology. Older adults must therefore learn the task-specific dimensions of their new emergent configuration space landscapes. This learning process is likely similar to that undergone by children during development, with the exception that unlike children, there are severe consequences to falling.

The influence of communication would be largest in people with cognitive deficits. We would expect that maintaining upright stance would be prioritized over communication and performing the upright task. However, populations with deficits in executive function, such as those with Parkinson's disease, may have problems with this prioritization and as a result suffer a fall. Indeed, it has been documented that older healthy adults will sometimes stop talking while walking, presumably because cognitive limitations preclude performing both activities and stability is prioritized (5). However, individuals with Parkinson's disease will not suspend talking while walking, despite the risk of doing both activities simultaneously (5).

Implications for Rehabilitation

As discussed above, to fully understand the role of training on multi-task activities, it is important to use assessments that are ecologically valid and similar to activities experienced in everyday life. For example, when visiting grandchildren, older adults often walk, talk, and step over toys. A walking, talking, and obstacle crossing task would mimic this real-world activity. Postural control should therefore be examined as a hierarchy of ecologically valid tasks with systematically increasing demands. This would allow for the development of configuration space diagrams expressed as a function of time or task phase. Hypotheses regarding the change in the configuration space regions could be developed. We argue that changes in adaptability and stability will be more relevant to the risk of falling than the magnitude of postural movements. Analysis of these diagrams, coupled with modeling work, would be informative for understanding the mechanisms underlying age-related instability.

The configuration space framework can be used to gain insight regarding the efficacy of training and may lead to the optimal design of new interventions. Typically, training efficacy is assessed using strength, sensory acuity, or standardized clinical measures, but it is not clear how these measures relate to improvements in overall disability or quality of life. The configuration space morphology would allow researchers and therapists to move beyond simple spatial or temporal measures to assess stability and may help explain some interesting findings in the training literature. For example, research has demonstrated that Tai Chi training appears to improve mobility and performance in clinical tests of balance (26). Interestingly, increased postural movements during a dynamic walking task have been observed (12). An increase in sway after training may appear counterintuitive from a

traditional perspective. However, the increase may be explained by a larger white area in the configuration space morphology.

In summary, declines in the ability to control posture based on the demands of a concurrent task may contribute to reduced stability, mobility, and quality of life in older individuals. Additionally, the efficacy of training paradigms should consider changes to the configuration space morphology and how these changes improve the ability of older adults to safely engage in tasks common to daily life.

CONCLUSIONS

Examining posture and balance within a task constraint framework can provide new insights regarding how upright posture is maintained. The ability to control posture based on the demands of a concurrent task emerges early in infancy and is refined into the second decade of life. Once postural dynamics are adult-like, the control of posture is complex, even when performing seemingly routine tasks such as carrying a load. Specifically, young adults appropriately change the degree of postural sway or alter the degree of body symmetry based on the demands of the task. The ability to control posture based on the demands of a concurrent task begins to decline in older adults, especially in those with cognitive decline, although there is some evidence that experience can delay this decline. The decline makes it more difficult to safely perform daily tasks, particularly when concurrently performing a cognitively demanding task such as communication. It is likely that to improve balance and reduce fall risk in older adults, training would need to focus on the best technique to improve the morphology of configuration space so that older individuals can safely perform multi-task activities common to daily life.

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Figure 1.

The body configurations (joint angles) about the ankle (x-axis) and hip joint (y-axis) that can be adopted while performing a standing manual fitting task. The manual task is placing an object through a large opening (left panel) or small opening (right panel). The black region represents body configurations where bipedal stance is not possible. The gray region represents configurations where bipedal stance is possible, but the manual task is not possible. The manual behavior is only possible using configurations in the white region. The black line within the white region represents the body movements that occur during the manual task. Figure inspired from (31). It should be noted that the configuration space diagrams could be constructed using joints other than the ankle and hip. In this paper, the ankle and hip are utilized because they are likely the main joints utilized in the movements depicted.

Figure 2.

Schematic of the changes that would occur in the configuration space morphology as a dynamic task (lifting, walking up stairs, carrying, grasping, and putting away groceries) is being performed. Task illustrations by Michele Rund.

Figure 3.

a) Typical base of support and center of pressure trajectory and b) TtC during the fitting task examined in (15). Each epoch of time is defined as 10% of the movement cycle (from grasping the block to block passing through the opening).

Figure 4. Configuration space of an older adult with cognitive decline performing a task (putting away groceries) without distraction (top row) or while communicating (bottom row). Task illustrations by Michele Rund.