THE INFLUENCE OF ATTENTIONAL FOCUS ON MOVEMENT VARIABILITY

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CHENG-JU HUNG

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DEDICATION

This dissertation is dedicated to my father, Ching-An Hung and my mother, Li-Chin Chou along with my grandparents (late) for their endless love, support and encouragement. Furthermore, I want to thank my sister, I-Hsien Hung for her loving support.

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ABSTRACT

CHENG-JU HUNG

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The advantage of an external focus over internal focus in performance outcomes is consistent in a large body of literature. Based on the constrained action hypothesis, an external focus may promote flexibility and adaptability in the motor system, which may result in higher movement variability. Limited previous evidence supports the claim that an external focus promotes more functional variability. Moreover, the previous studies also suggested that task difficulty may modulate the effect of attentional focus. The purpose of current study was to investigate the influences of attentional focus (external focus and internal focus) and the level of task difficulty on movement variability (*SD* of joint angles, goal-equivalent variability [V_{UCM}], non goal-equivalent variability [V_{ORT}]) as well as performance (COP trajectory) during a task involving standing and squatting on inflatable balancing discs.

Young, healthy adults ($N = 36$) balanced on inflatable discs while standing (low difficulty) and holding squat (high difficulty). For each level of difficulty, they completed three 10-s trials for each focus condition (baseline [no instruction provided], internal focus, and external focus). The order of task difficulty was counterbalanced and the focus condition order was randomized. Kinematic and COP data were captured by 9 Vicon infrared cameras (250 Hz) and 2 AMTI force plates. Separate factorial MANOVAs assessed differences due to focus and difficulty for COP trajectory (*SD* of COP in anterior/posterior and medial/lateral directions, COP_X & COP_Y) and movement variability as assessed by *SD* of joint angles and uncontrolled manifold analysis

(UCM, V_{UCM} & V_{ORT}). Sidak post-hoc tests were used for pairwise comparisons. Results showed there was a reduction of postural sway in the anterior/posterior direction (COP_X) in external focus compared to internal focus and baseline (p = .024, p < .001, respectively). An external focus also decreased the *SD* of the ankle relative to baseline in the easier version of task (p = .003), and lowered the *SD* of knee and hip with reference to baseline across two level of difficulties (p = .050, p = .003, respectively). UCM measures showed no differences between an external focus and internal focus, but there was a reduction of V_{UCM} in the external focus condition compared to baseline (p =.009). While behavioral benefits of an external focus are consistent with previous research, the hypothesis that an external focus promotes greater functional variability was not supported, requiring further study with an array of motor tasks to determine the veracity of the claim.

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CHAPTER I

INTRODUCTION

Attentional focus (i.e., what a person thinks about while performing a motor task) has been widely applied and tested in sport and clinical research. The majority of studies suggest that directing attention externally (i.e., to the effects of movement outside his or her body) improves the learning and performance of motor skills compared to internally (i.e., on the movement of body parts; Neumann, 2019; Vaz et al., 2019; Vidal et al., 2018; Wulf, 2013). The benefit of an external focus has been reproduced widely in a variety of types of skills including balance (Shea & Wulf, 1999; Wulf et al., 1998), standing long jumps (Becker & Smith, 2015; Porter et al., 2010), vertical jumps (Wulf, Zachry et al., 2007), dart throwing (Lohse et al., 2010; Marchant et al., 2009), basketball free throw shooting (Al-Abood et al., 2002; Zachry et al., 2005), golf pitch shots (Wulf et al., 1999; Wulf & Su, 2007), and soccer kicks (Wulf et al., 2002).

To explain the mechanism of the external focus advantage, the constrained action hypothesis (McNevin et al., 2003) has been widely cited in previous literature. McNevin et al. (2003) hypothesized that an external focus could coordinate the movement at a more automatic level and consequently facilitate movement efficiency, while an internal focus may disrupt this automaticity of movement organization because of more conscious control involvement. Studies using the dual-task paradigm found that an external focus demonstrated less conscious interference in the control processes while the movement performance were improved and fluent, implying a higher degree of automaticity (Kal et al., 2013; Wulf, McNevin & Shea, 2001). Results from electromyography (EMG) studies support this statement by demonstrating increased neuromuscular efficiency characterized by decreased muscle co-contraction patterns (Lohse & Sherwood, 2012), as well as increased force production with lower activation (Marchant et al., 2009) while employing an external focus.

Among the different categories of motor skills, balancing tasks have drawn a great deal of interest for researchers in attentional focus studies. These studies have included tasks such as using a ski simulator (Wulf et al., 1998), stabilometer (Chiviacowsky et al., 2010; Jackson & Holmes, 2011; McNevin et al., 2003; Pashabadi et al., 2014; Shea & Wulf, 1999; Wulf et al., 1998; Wulf & McNevin, 2003; Wulf, McNevin & Shea, 2001; Wulf, Shea, & Park, 2001; Wulf et al., 2003), quiet standing (McNevin & Wulf, 2002; Rhea et al., 2018; Wulf, Töllner, & Shea, 2007), and standing on a foam or balance disc (Wulf, 2008; Wulf et al., 2009; Wulf et al., 2004; Wulf, Töllner, & Shea, 2007). Most studies using a stabilometer (a stability platform that would tilt to right and left side from the horizontal level) showed similar results (i.e., smaller root mean square error (RMSE) of the platform deviation in favor to an external focus; McNevin et al., 2003; Wulf et al., 1998; Wulf & McNevin, 2003; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001). For standing on the foam or balance discs, a smaller *SD* of center of pressure (COP) trajectory or RMSE of COP trajectory was observed. The positive effect of an external focus during balancing tasks has also been generalized to different populations such as older adults (Chiviacowsky et al., 2010), post-stroke patients with good to moderate trunk control (Mückel & Mehrholz, 2014), adults with Parkinson's disease (Landers et al., 2005; Wulf et al., 2009), and adults recovering from ankle sprains (Laufer et al., 2007; Rotem-Lehrer & Laufer, 2007).

Although the benefit of an external focus on balance is widely reported, this claim is not supported by some studies. In expert acrobats, both an internal and external focus had a detrimental impact on the balance performance relative to a control condition (Wulf, 2008). In individuals with Parkinson's disease, a recent study did not show any benefit of combined attentional focus instructions and a balance training program compared to a control group (Landers et al., 2016). A study with young adults performing quiet standing (Polskaia et al., 2015) also revealed no difference in postural sway between an internal and external focus. Another study with a sample of older adults implied no learning differences between internal and external training groups while practicing dynamic balance (De Bruin et al., 2009). In considering these null findings, a possible explanation for the lack of effect is the subjective task difficulty relative to each specific population. Previous research suggests that attentional focus effects only emerge when a task is sufficiently challenging (Wulf, Töllner, & Shea, 2007). Quiet standing for general healthy adults, balancing on the rubber discs for elite acrobats, and training for Parkinson’s disease patients with sufficient balance may create a low difficulty demand meaning participants could already reach a high degree of automaticity in movement control. Since the proposed benefit of an external focus includes enhanced automaticity, when tasks are already simple enough to perform automatically, an additional benefit may not be expected.

In measuring the impact of attentional focus on balancing tasks, most studies have used traditional measures of movement variability such as the standard deviation of center of pressure trace, or RMSE of platform angles. In general, movement variability is described as the variations in motor performance across multiple repetitions (Stergiou et al., 2006), and the interpretation of its role in motor performance and learning has been controversial in terms of quality of human movement. Illustrated in Bernstein's (1967) classic study, reasonable variability was observed for individual joints of the upper extremity while the hammer tip of each strike was consistent. An early study examining the learning of a ski-simulator task also claimed that degrees of freedom were released (angular movement significantly increased) with practice; consequently, the amplitude of joint motions gradually increased (Vereijken et al., 1992). More recent views of movement variability (Stergiou et al., 2006) suggest that encouraging participants to perform identical movement patterns may simply induce inflexible motor behavior and reduce the ability to transfer to different tasks or changing environmental demands (Stergiou & Decker, 2011). In one study performing a dart-throwing task, less absolute error and increased shoulder joint variability under an external focus relative to an internal focus suggests that movement variability is associated with a better movement outcome (Lohse et al., 2010). Another study (Wulf & Dufek, 2009) found no correlation between joint moments when using an external focus while performing a vertical jump, whereas an internal focus showed a similar pattern between the joints, assumedly by freezing their degrees of freedom to restrain the adaptable utilization of joints (Vereijken et al., 1992). The results inferred that freeing the degrees of freedom enabled the motor system to select flexible movement solutions that subsequently increase the movement variability. These results have led researchers to suggest that an external focus may promote more functional variability (Wulf, 2013).

There are a variety of ways of measuring variability. Standard deviation (*SD*) or range is a traditional variability measure that provides a description of the amount or magnitude of the variability. Lohse et al. (2010) examined the shoulder and elbow joint angles during dart throwing, and the results demonstrated greater shoulder joint variability with an external focus compared to an internal focus. However, this traditional measure only provides the magnitude of variability without examining the structure of the variability. Even as the magnitude of variability increased, the structure or organization of variability may be decreased (Harbourne & Stergiou, 2009). For structural variability, several non-linear approaches have been used. Entropy is one common analysis method in the biological signals, and describes the uncertainty or regularity of a movement in a given time series. Several studies have adopted an entropy approach to investigate how attentional focus influences the structure of movement variability. Diverse results have been found due to considerably different methods and analysis techniques (Rhea et al., 2018; Vaz et al., 2019). Recently, a modified vector coding technique was used to evaluate the influence of attentional focus on lower extremity coordination variability during a standing long jump. Interestingly, no effect of attentional focus on coordination variability was observed (Vidal et al., 2018). The loss of higher-order information of joint coordination may result in an insensitive ability to detect differences.

To overcome the limitation, uncontrolled manifold (UCM) analysis offers a promising tool to understand the structure of variability involved in multiple joints/segments. UCM separates variability into goal-equivalent (V_{UCM}) and non-goal-equivalent (V_{ORT}) components. V_{UCM} is the variance along with a sub-space (UCM) that does not affect task-specific performance variables, whereas V_{ORT} is variance orthogonal to the UCM that influences or destabilizes the performance variables (Scholz & Schöner, 1999). Recently, UCM has been used to investigate movement variability with respect to controlling the leg orientation and vertical leg length during hopping in place while using an internal or external focus of attention (Fietzer et al., 2018). Unexpectedly, both an internal and external focus decreased leg orientation stabilization during takeoff compared to a no focus condition. However, an external focus demonstrated larger leg length stabilization than an internal focus during the hopping stand phase. With both studies (Fietzer et al., 2018; Vidal et al., 2018), the standing long jump and hopping in place are discrete tasks with definite start and end points. The short duration of those tasks may require less range of variability to accommodate for the environment to achieve the task goal. UCM may detect the effect of the attentional focus on movement variability under appropriate selection of performance outcome variables and with appropriately challenging tasks.

Balance requires continuous coordination and adjustment of the body segments in relation to the environment to maintain the body's center of mass (COM) over either a static or unfixed base of support without falling (Shumway-Cook & Woollacott, 2001; Winter et al., 1990). Balancing tasks have been broadly utilized in various areas both in research and clinical practice, and balance is also a critical element to achieve in fundamental and advanced motor skills (Kim et al., 2017). The levels of difficulty for balancing tasks depends on the size of base of support or the sway amplitude of COM relative to the base of support during the task, and the background of participants. Although quiet standing and balancing on a stabilometer have been used in a large body of attentional focus studies, the use of balance discs is another option that provide advantages. First, a simple task such as quiet standing may be not challenging enough to take advantage of external focus (Wulf, Töllner, & Shea, 2007). Second, balancing on a stabilometer is not representative of daily living demands, whereas standing on balance discs is more related to our regular activity. Balance discs also have been widely used in physical therapy for training.

The limited number of studies measuring how movement variability is influenced by attentional focus have produced rather inconclusive findings. This could be due to inadequate tasks (discrete movement), insufficient sensitivity detecting the differences, and problematic selection of performance variables. With this limited evidence, the claim that an external focus promotes more functional variability remains debatable. Due to the limitations of previous studies, utilizing a UCM approach to investigate the effect of attentional focus on the structure of movement variability with respect to controlling the COM while balancing with various levels of difficulty is warranted.

Purpose of the Study

The purpose of the study is to investigate the effects of attentional focus (external and internal focus) and the level of task difficulty on movement variability (*SD* of joint angles, V_{UCM}, V_{ORT}) as well as performance (COP trajectory) during a task involving standing and squatting on inflatable balancing discs.

Research Hypotheses

1. Focus condition and task difficulty will influence the *SD* of COP trajectory in the X and Y direction as well as 95% confidence-ellipse area of COP trajectory when balancing on inflatable balancing discs
2. Focus condition and task difficulty will influence the *SD* of joint angles (ankle, knee, hip, L4/L5, C7 orientation angle in the sagittal plane) when balancing on inflatable balancing discs.
3. Focus condition and task difficulty will influence the V_{UCM} and V_{ORT} when balancing on inflatable balancing discs.

Significance of the Study

The mechanism of how an external focus benefits motor performance is still under investigation. The majority of attentional focus studies only report performance-related measures with only a few studies investigating the movement variability resulting from attentional focus, which may explain the cause. This study will delve into the movement variability involved in multiple joints or body segments during the balancing task. It is expected that the results will reassess or even reinforce the constrained action hypothesis.

This study also has practical significance. Evidence has shown that poor balance can cause falls or injuries (Shumway-Cook et al., 2009; Ward et al., 2015). Fall prevention is one of the vital topics in clinical settings. Studies have found that physical therapists frequently reassure patients to be conscious of their movements (internal focus; Johnson et al., 2013). This approach may reduce automaticity according to the constrained action hypothesis. The results of this study would provide the practitioners insight of instruction on the balance training to improve the performance or facilitate the learning progress.

Assumptions

1. The segments are rigid.
2. The pressure of the balance disc remains constant during all the trials.
3. The body posture is symmetric.
4. Participants are compliant with the different verbal instructions trial by trial.

Delimitations

1. We excluded participants over the age of 44 to limit the confounding variables such as aging effects in the study.
2. We excluded participants with experience using balance discs to minimize the effect of different skill levels of balance.
3. Participants stood on the balance discs barefoot to eliminate the effects of different type of shoes.
4. Testing was conducted in a laboratory setting.

Limitations

1. We only examined the sagittal plane motion because the movement is predominantly performed in this plane.
2. We could not be absolutely certain that participants complied with instructions. In this experiment, we repeated the instruction before each trial to maximize the participant's compliance.

Definition of Terms

1. Attentional focus: the focus of an individual's attention at a particular moment. This focus could be internal (i.e., on the movement of body parts) or external (i.e., to the effects of movement outside his or her body).
2. Constrained action hypothesis: a hypothesis aimed to explain the mechanism of advantage of external focus that stated that by reducing their active intervention into control processes governing performance would promote the more effective and normal reciprocation between voluntary and reflexive control processes to emerge (McNevin et al., 2003; Wulf, McNevin & Shea, 2001).
3. Center of mass (COM): the balanced point of a body that represents the location at which gravity is assumed to act.
4. Center of pressure (COP): the point on the ground where the resultant of all ground reaction forces acts. This point also represents the distribution of force between both feet and between the front and rear part of the feet.
5. Degree of freedom: the number of values involved in the movement system that have the freedom to vary. For example, the shoulder joint, a ball and socket type joint that allows three planes of motion, has three degrees of freedom.
6. Movement variability: the normal variations that occur in motor performance across multiple repetitions of a task
7. Uncontrolled manifold (UCM): a concept to use joint space as the conceptual space in which all variance is measured. The UCM contains all the combinations of joint angles that are consistent with one particular performance outcome. There is such an UCM for any performance outcome. Hypothetically, at any given point during the movement, joint configurations vary primarily within UCM.

8. Global reference frame: the laboratory coordinate system in which body marker coordinates are calculated.
9. Local reference frame: the reference frames embedded to a body segment and expressed relative to the global reference frame.
10. Orientation angles: the angles about the coordinate axes that are formed by a segment with respect to its proximal segment

CHAPTER II

LITERATURE REVIEW

Attentional Focus

Facilitation and enhancement of learning a motor skill and performance is a common objective in different fields such as kinesiology, sports, and physical therapy. Providing the right instruction to the learner that directs the learner's attentional focus plays a key role to optimize learning and performance of a motor skill (Wulf et al., 1998). The instructions could induce the learner to focus their attention inwardly on the body movement (internal focus), which is frequently observed in athletic coaching and instructing patients in clinical practice (Durham et al., 2009; Johnson et al., 2013). Alternatively, instructions could guide the learner to directly focus on the movement effect toward the environment or outside the body (external focus; McNevin, Weir, & Quinn, 2013; Peh et al., 2011; Wulf, 2013; Wulf et al., 1998).

For decades, the advantage of an external focus of attention over an internal focus has been well documented across a wide variety of skill performance and sports activity including balance (e.g., standing on the stabilometer or inflated discs), golf pitch shot (Wulf et al., 1999; Wulf & Su, 2007) and putting (Poolton et al., 2006), volleyball serve, soccer kick (Wulf et al., 2002), basketball free throw (Al-Abood et al., 2002; Perreault & French, 2015; Zachry et al., 2005), dart throwing (Lohse et al., 2010), vertical jumps (Wulf & Dufek, 2009; Wulf, Zachry, et al., 2007), and standing long jumps (Porter et al., 2010; Wu et al., 2012). However, the theoretical understanding of the underlying mechanisms leading to an external focus advantage are still developing. The following sections summarize the results of various types of research in attentional focus, describe current theoretical viewpoints, and consider how movement variability might contribute to a deeper understanding of attentional focus effects.

The effect of attentional focus on balance

Attentional focus has been tested in balance tasks. Most evidence demonstrates that an external focus of attention enhances learning more than internal focus (McNevin et al., 2003; Wulf et al., 1998; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001). A meta-analysis (Kim et al., 2017) examined the effects of external and internal focus on balance during the practice, retention, and transfer phases. The overall results suggest that for all phases, external focus is more beneficial than internal focus for improving balancing performance. Among attentional focus studies examining balance, a stabilometer was the most common instrument used for testing balance. The stabilometer consists of a wooden platform attached to a support structure by two freely rotating axles which allows the platform to deviate in either direction (see Figure 1). When participants direct their attention externally when balancing on the stabilometer (i.e., focus on minimizing the movements of the platform), they experience less deviation of the platform (smaller RMSE degree) compared to internal focus (i.e., keeping the feet horizontal; Wulf, Shea, & Park, 2001).

Figure 1

Stabilometer

Several motor learning studies have shown less RMSE of angular displacement of the platform with an external focus compared to an internal focus during the retention phase (Wulf et al., 1998) and concurrent feedback also adds an additional benefit if implemented with an external focus during balancing (Shea & Wulf, 1999). One study (Wulf, McNevin, & Shea, 2001) used a dual-task approach (response to auditory stimulus as secondary task) to investigate the mechanism of attentional focus. The results showed that an external focus decreased RMSE and attention demands (secondary task probe reaction time) relative to an internal focus, supporting the idea that using an external focus results in a decreased attentional demand relative to an internal focus, perhaps by allowing the motor system to self-organize at a more subconscious level. Another study also found that instructions that induce an external focus toward a suprapostural task (e.g., focus on the tube with table tennis ball inside without ball contacting each end of tube) was more beneficial for both the suprapostural and postural (balance) aspects of the skill (Wulf et al., 2003).

While the benefit of an external focus in balance tasks has been widely reproduced, several studies have also reported no significant benefit of external focus versus internal focus (De Bruin et al., 2009; Wulf, 2008). The population from those studies were much different from others. Specifically, these two studies used participants who were 70 years or older (De Bruin et al., 2009); and world-class acrobats (Wulf, 2008). Another interesting finding also showed that the effects of attentional focus on healthy children and adults are similar, but task complexity and sex moderate these effects (Becker & Smith, 2013). In considering these three findings, one thing that may impact the results is subjective task difficulty. Previous research has suggested that attentional focus effects do not emerge when tasks are not sufficiently challenging because the task can be performed relatively automatically (Wulf, Töllner, & Shea, 2007). For world-class acrobats, standing on an inflatable disc could be perceived as relatively easy. Becker and Smith (2013) also reported that with two versions of the same task varying in difficulty, external focus benefits were only found with the more difficult version of the task. Finally, for adults over 70, task difficulty may be difficult to determine since that group is likely much more heterogeneous in terms of motor system health. Thus, to examine the mechanisms underlying the external focus benefit, it appears critical to identify an appropriately challenging motor task.

Table 1

Studies Examining the Effect of Attentional Focus on Balance

Study	Task	Main outcome measures	Group/Conditions	Results
(Wulf et al., 1998) Experiment I	Ski-simulator	movement amplitude/ frequency	IF, EF, C	EF > IF, C
(Wulf et al., 1998) Experiment II	Stabilometer	root- mean-square error (RMSE) (degrees)	EF, IF	EF > IF
(Shea & Wulf, 1999)	Stabilometer	RMSE	EF, IF	EF > IF
(Wulf, McNevin, & Shea, 2001)	Stabilometer	RMSE, MPF, probe RT	EF, IF	EF > IF

(Wulf, Shea, & Park, 2001) Experiment I	Stabilometer	RMSE, MPF	EF, IF	EF > IF (retention)
(Wulf, Shea, & Park, 2001) Experiment II	Stabilometer	RMSE, MPF	EF, IF	EF > IF (retention)
(Wulf & McNevin, 2003)	Stabilometer	RMSE	EF, IF, C	EF > IF, C
(McNevin et al., 2003)	Stabilometer	RMSE	EF, IF (far-outside, far-inside, near internal)	EF > IF (retention)
(Wulf et al., 2003) Experiment I	Stabilometer	RMSE, Number of errors	EF, IF	EF > IF (retention & transfer)

(Wulf et al., 2003) Experiment II	Stabilometer	RMSE	EF, IF, C	EF > IF (retention & transfer) EF > IF, C (transfer)
(Chiviacowsky et al., 2010)	Stabilometer	Time in balance	EF, IF (aged between 60-85)	EF > IF
(Jackson & Holmes, 2011)	Stabilometer	RMSE	IF/feet, IF/board, EF/feet, EF/board	EF > IF in acquisition while the task also external
(Pashabadi et al., 2014)	Stabilometer	Biodex, stabilometer, EMG	EF, IF (10 gymnasts)	EF > IF
(McNevin & Wulf, 2002)	stand quietly on a force platform	Postural sway (COP MWSD) .MPF	EF, IF, C	EF > IF

(Wulf et al., 2004)	Balance (inflated disk) and supra-postural task	Magnitude of Sway (RMSE) Frequency of Responding (MPF)	EF (disk) or IF (feet) on postural task, and EF (pole) or IF (hands) on the suprapostural task. Thirty-two university students	EF > IF
(Landers et al., 2005)	Balance Master	Balance equilibrium scores from three computerized dynamic posturography conditions.	EF, IF, C Twenty-two subjects diagnosed with idiopathic Parkinson's disease	EF > IF, C
(Wulf, 2008)	inflated disk on the force platform	RMSE and MPF of the COP	EF, IF, C Twelve world-class acrobats	C > EF, IF

(Wulf et al., 2009)	inflated rubber disk on the force platform	RMSE of the COP	EF, IF, C Fourteen participants diagnosed with idiopathic PD	EF > IF, C
(De Bruin et al., 2009)	Biodex Balance System (5-week balance training)	Weight shifting score and dynamic balance parameters (Biodex Balance System)	EF, IF 26 older persons (81 ± 6 years)	EF = IF
(Laufer et al., 2007)	Biodex Stability System. (ten 20-second trials, performed on 3 consecutive days)	Overall Stability Index (OSI); Anterior/Posterior Stability Index (APSI); Medial/Lateral Stability Index (MLSI) from Biodex Balance System)	EF, IF Forty young adults with a grade 1 or 2 ankle sprain	EF > IF (retention)

(Rotem-Lehrer & Laufer, 2007)	Biodex Stability System. (ten 20-second trials, performed on 3 consecutive days)	OSI; APSI; MLSI from Biodex Balance System)	EF, IF 36 young adults with a grade 1 or 2 ankle sprain	EF > IF (transfer)
(Becker & Smith, 2013)	Double Pedalo	Total time taken to travel 7m	EF, IF 48 Undergraduate 48 Children	EF = IF (simple task) EF > IF (complex task only for males)

Abbreviations: C, control; EF, external focus; IF, internal focus

Measurement in Attentional Focus Research

Measures related to movement outcomes

Movement outcomes related to error is the most common measurement to determinate the effect of attentional focus especially if the task goal is balance or accuracy demanding. For a discrete task such as dart throwing, golf pitch shots, basketball free throws, soccer kicking, measures of spatial error are often used (Al-Abood et al., 2002; Lohse et al., 2010; Wulf et al., 2002; Wulf & Su, 2007). For balancing, a continuous task, the RMSE and *SD* are often used to quantify the balance performance (Shea & Wulf, 1999; Wulf et al., 1998; Wulf & McNevin, 2003).

A decrease in RMSE or *SD* is typically interpreted as less error during performance, therefore better postural control. *SD* is also the magnitude of variability, showing how the outcome is distributed in a given time period, where a large spread (larger *SD*) indicates less controlled behavior. Although the *SD* and RMSE are an overall representation of the outcome goal, the difference between *SD* and RMSE is that *SD* shows the spread relative to overall mean of the outcome, whereas the RMSE displays the error based on the target point or number. It should be noted that lower *SD* or RMSE of the performance outcome is the task goal and should not be confused with the movement variability. There is more discussion on this in the later section.

Measures related to movement production

There are several ways to quantify the effects of attentional focus. Most previous studies have focused mainly on the outcome of the movement. The kinematic analysis is one of most common way to describe the human motion in numerical fashion that would provide more objective results for assessing the effect of attentional focus on the human movement itself.

An et al. (2013) used three-dimensional (3D) motion capture to determine whether an external focus increased the rotation angle of the shoulders relative to the pelvis (X-factor stretch) in novice golfers. Greater X-factor stretch, and higher maximum angular velocities of the wrist, shoulder, and pelvis were found in those who were asked to focus externally compared to those who were asked to focus internally. Zentgraf and Munzert (2009) also examined the kinematic differences in juggling among control, internal, and external focus conditions. The external group reduced the height discrepancy between the ball peaks compared with the internal. On the other hand, the internal group decreased elbow displacement in tossing compared with the external and the control group. The data demonstrated that specific direction of attention could influence the movement patterns of participants.

The benefits of an external focus on movement kinematics have also been applied in the clinical practice setting such as orthopedics and rehabilitation (Gokeler et al., 2015). Gokeler et al. (2015) assessed the sagittal plane knee kinematics in anterior cruciate ligament (ACL) reconstruction patients while performing a series of single-leg hops for distance using either an external focus or an internal focus. Results revealed that there were significantly larger knee flexion angles at initial contact with an external focus compared to internal focus. Also, an external focus promoted larger peak knee flexion, greater total range of motion, and increased time to peak knee flexion for the injured leg which enhanced a safer landing pattern and may reduce second ACL injury risk consequently.

Measures related to muscle activation

Besides kinematic analysis, using EMG measurement to monitor the muscle activation for explaining the cause of movement have also been implemented in the study of attentional focus (Marchant et al., 2008; Vance et al., 2004; Wulf et al, 2010; Zachry et al., 2005). Generally, the results have shown that an external focus led to a more efficient muscular contraction and was correlated to better motor performance than an internal focus. More specifically, in two studies, participants performed biceps curls and demonstrated reduced EMG activity and faster movement with an external focus while focusing on the movements of the curl bar (Marchant et al., 2009; Vance et al., 2004). Another study investigated basketball free throws. The findings showed that free-throw accuracy was higher in an external focus while EMG activity of biceps and triceps muscle was lower (Zachry et al., 2005). These results suggested that using an external focus facilitates effective and efficient neuromuscular recruitment.

Measures related to movement variability

While the majority of early attentional focus studies only report performance outcome measures, some researchers have also looked into measures that describe movement patterns, intending to explain the mechanism of attentional focus. A study on throwing darts found that an external focus led to less absolute error of throwing while variability for shoulder kinematic from motion analysis were also increased relative to an internal focus (Lohse et al., 2010). More recently, a study on standing long jump used a modified vector coding method to investigate the variability in intersegmental coordination due to the attentional focus (Vidal et al., 2018). Interestingly, while greater jump distances were found in an external focus, there were no differences of inter-joint variability between focus conditions. Although Vidal et al. (2018) suggested that attentional focus may not directly influence movement coordination conditions, there were possible reasons for not discovering the variability changes. The later part of this chapter discusses this issue in more depth.

Theoretical Explanation of Attentional Focus - Constrained Action Hypothesis

The most widely cited mechanism to explain the external focus advantage is the constrained action hypothesis (McNevin et al., 2003). According to the constrained action hypothesis, an external focus would facilitate movement efficiency by promoting movement organization at a more automatic level, while an internal focus may involve more conscious control of effectors and consequently disrupts the automaticity of coordination processes.

A study (Wulf, McNevin, & Shea, 2001) using a dual-task approach showed that an external focus improved balance performance (primary task) and decreased the attention demands relative to an internal focus. Similar findings also reported that golf putting while adopting an external focus were more robust and consistent when executing a tone counting task at the same time comparerd to internal focus (Poolton et al., 2006). Those combined results implied that an external focus required less cognitive resources, and could potentially be interpreted as allowing the movement to more naturally self-organize.

Another assessment of automatization is from the movement execution perspective. Results of studies using EMG support the constrained action hypothesis by demonstrating reduced agonist/antagonist co-contraction when using an external focus (Lohse & Sherwood, 2012), as well as greater force production with lower activation (Marchant et al., 2009). Improved movement regularity and fluency characterized by sample entropy (SaEn) and dimensionless jerk have also been observed with an external relative to an internal focus (Kal et al., 2013).

Movement Variability

Movement variability has been described as the variations in motor performance across multiple repetitions (Stergiou et al., 2006). Why is there variability in human movement? The main reason is that there is huge number of degrees of freedom in the human motor system that self-organize each time a movement is executed. As expressed by Bernstein (1967), the concept of repetition without repetition, no two repetitions will be identical when repeating a movement task for the reason that each movement involves unique non-neural and motor patterns. Illustrated in Bernstein's (1967) classic study, the movement of professional blacksmiths repeatedly hitting a chisel is a multi-joint task that requires precision of an ending point. Reasonable variability was observed for individual joints of the upper extremity; nevertheless, the hammer tip of each strike was consistent. A study involving the learning of a ski-simulator task also claimed that the degrees of freedom was released with practice; consequently, the amplitude of joint motions gradually increased (Vereijken et al., 1992). Similar features have been found in skilled golfers. Although gender differences were found in movement variability for the thorax and pelvis, both genders achieved similarly low levels of clubhead trajectory variability during the downswing (Horan et al., 2011).

Historically, movement variability has been considered as noise and error, which are thought to be random and independent. For years, some health practitioners have attempted to reduce patients' variability during performance of movement tasks by correcting their pattern and asking them to perform repeatedly with the aim of achieving a consistent or normal pattern. A more recent viewpoint of movement variability (Stergiou et al., 2006) suggests that encouraging people to perform the same movement patterns may simply induce an inflexible motor behavior and reduce the ability to transfer to different tasks or changing environmental demands (Stergiou & Decker, 2011).

Higher movement variability of skilled performers is indicative of the ability to adapt to constraints and perturbations, resulting in the flexibility and adaptability to operate proficiently in creating a movement. This is also consistent with the explanation of the advantage of external focus from the constrained action hypothesis. In that, the evidence has led researchers to suggest that an external focus may promote more functional variability (Wulf, 2013), though empirical evidence for this claim is currently limited. One study (Wulf & Dufek, 2009), through a between-participant analyses, found that the correlations between joint moments (ankle–knee; ankle–hip; knee–hip) were all significant in the internal focus, but none of those correlations were significant in the external focus condition while performing a jump-and-reach task. The results suggested that participants responded in a similar pattern when instructed to focus on their finger (internal focus), presumably by freezing their degrees of freedom (Vereijken et al., 1992). In contrast, focusing on the rungs (external focus) seemed to have a tendency to free the degrees of freedom that enabled the motor system to automatically utilize more flexible movement solutions, and subsequently it may increase the movement variability.

In a recent study, expert and novice law enforcement officers were asked to perform a handgun shooting task using a dual-task paradigm (Raisbeck et al., 2016). The results showed that the upper arm of between-trial variability increased during dual-tasks compared to control among the expert group, but shooting accuracy and consistency were similar across all three conditions. In contrast, less changes in movement kinematics were observed in the novice group. However, their performance was poorer during both dual-tasks relative to control. The data implied that conditions required attentional demands may promote the adaptation in variation of movement to maintain end-point control for experts. The results are also in line with a study examining attentional focus effects on dart throwing which found that greater variability of shoulder movement at the moment of release when participants used an external than internal focus (Lohse et al., 2010). Increased variability during an external focus of attention would be similar to the expert property, “adaptive variability” (Seifert et al., 2013). This variability allows the movement to be adopted in a functional way and not fixed into a rigidly stable solution when adjustment for changes in dynamic environment is needed (Davids et al., 2003).

Measurement of Movement Variablity

Traditional approach

Traditionally, the variability in measurement has often been quantified using one or more of five descriptive statistics: range, interquartile range, variance, coefficient of variation and, most commonly, *SD*, which are all based on a single statistic. There were several studies using the *SD* to identify the degrees of freedom that are frozen out in early stage of learning and subsequently released over practice (Caillou et al., 2002; Vereijken et al., 1992). However, the *SD* alone is sometimes not adequate because it depends on the magnitude of the mean. Subsequently, it may not be appropriate for direct comparison between studies. Therefore, in some instances, the coefficient of variation may be a better measure of variability as it has been normalized by the mean. *SD* gives a measure of absolute variability, whereas the coefficient of variation gives a measure of relative variability.

SD of a single body part provides limited information. To solve the issue of providing a measure of the variability of coordination between body segments, many techniques have been presented in the literature such as *SD* of relative motion angles (Heiderscheit et al., 2002) and coupling angle variability from a vector coding technique. A recent study implemented the coupling angle variability through modified vector coding technique to investigate the effects of focus of attention on movement coordination and coordination variability in the lower extremity while performing standing long jumps (Vidal et al., 2018). Unexpectedly, results suggested that attentional focus may not directly influence movement coordination variability. They claimed that the coordination patterns stayed consistent throughout the jumping movement until take-off. However, this may be due to the limitation of the modified vector coding technique, which only allows two joints in the analysis. There was a similar limitation for correlation or cross-correlation between joints, which has been also used to investigate the independency of paired joints (Caillou et al., 2002; Vereijken et al., 1992; Wulf & Dufek, 2009). The value for correlation only reflects the relationship between two variables; consequently, insufficient information of joint coordination patterns or the structure of the variability could be provided.

Contemporary approach

Corresponding to Bernstein's (1967) view point that humans control their redundant degree of freedom by using joint coordination, there are more degree of freedom available for any particular task than strictly needed. Accordingly, redundant elements (motor elements) can be varied without affecting the variables that must be maintained in order to achieve the task (performance variables). To put it simply, the human central nervous system conducts a series of solutions able to achieve the task without much deviation as described by Latash's Principle of Abundance (Gelfand & Latash, 1998). Therefore, joint coordination, which involves multiple motor elements, can flexibly stabilize the performance variables. For the purpose to solve the limitation of traditional measurement of variability and to quantify the joint coordination of human movements, UCM analysis has been proposed (Scholz & Schöner, 1999).

The uncontrolled manifold hypothesis

The UCM hypothesis (Scholz & Schöner, 1999) provides a framework to quantify joint coordination. Based on this framework, the variance among repetitions in a redundant space of element variables is decomposed into two components. One component of variance (V_{UCM}) along with a sub-space (UCM) does not affect task-specific performance variables. In contrast, another variance component (V_{ORT}) orthogonal to the UCM does influence or destabilize the performance variables. The synergy index (SI), a ratio of the normalized magnitudes of variance, is computed as $\frac{V_{UCM}-V_{ORT}}{V_{UCM}+V_{ORT}}$ (Latash, 2010). Higher values of V_{UCM} compared to V_{ORT} (larger SI) indicates more flexibility and reveals that each elemental variable collaborates together to minimize deviations of the performance variable from its desired goal. If SI = 0, we can conclude that the elemental variables do not stabilize the performance variable.

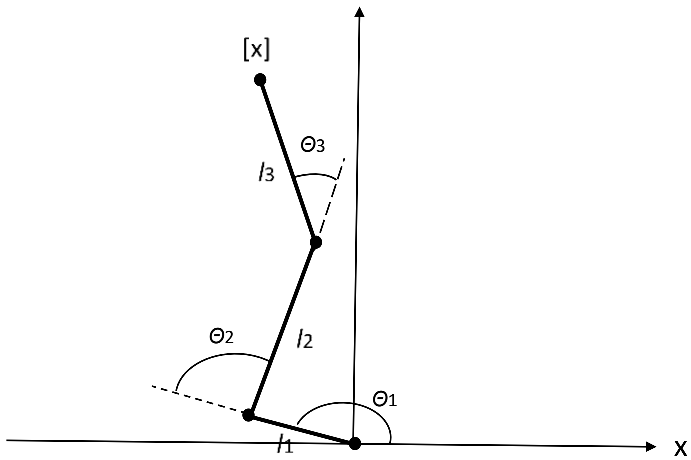
For the variance decomposition, the first step is to identify the sub-space manifold (UCM) containing all solutions that are equally able to perform the motor task in the elemental variable space. To do this, it is essential to establish a model of the relation between all elemental variables and the performance variables. For example, Figure 2 is a geometric three-limb chain model in the sagittal plane which represents the lower extremity in standing with stabilizing hip joint in anterior-posterial direction (x-axis). The elemental variables are the joint angles ($\theta 1$, $\theta 2$, $\theta 3$), and the performance variable is the end-point position of the hip joint described in the Cartesian coordinate as [x] which is a function of elemental variables:

$$[x] = f(\theta 1, \theta 2, \theta 3) = [\, l1 \cos \theta 1 + l2 \cos(\theta 1 + \theta 2) + l3 \cos(\theta 1 + \theta 2 + \theta 3)] \qquad (1)$$

where $l1$, $l2$, and $l3$ are the respective lengths of lower extremity segments. Note that the larger number of elemental variables (three joint angles in this example) than the number of performance variables (one coordinate) makes this model as a redundant motor system.

Figure 2

Geometric three-limb chain model



The Cartesian coordinate [x] denotes the position of the hip joint. Joint angle between segments are ($\boldsymbol{\theta}$1, $\boldsymbol{\theta}$2, $\boldsymbol{\theta}$3). Segmental lengths are *l*1, *l*2, and *l*3, respectively.

A manifold of this end-point position [x] in the joint angle space is a curve due to the non -linear geometric model (see Equation 1). For variance decomposition, the direction perpendicular to the curve needs to be defined and averaged joint configuration [$\bar{\boldsymbol{\theta}}$], = ($\bar{\boldsymbol{\theta}}_1$, $\bar{\boldsymbol{\theta}}_2$, $\bar{\boldsymbol{\theta}}_3$,) across repetition at the same portion of the movements is computed. The directions tangential to the curve at the average joint configuration will span the null space of the partial derivative of the performance variable with respect to each elemental variable (the Jacobian matrix). In this example, the Jacobian matrix of equation 1 is a 1-by-3 matrix.

$$J(\bar{\boldsymbol{\theta}}) = [-l1 \sin \bar{\boldsymbol{\theta}}_1 ,\ -l2 \sin \bar{\boldsymbol{\theta}}_2 ,\ -l3 \sin \bar{\boldsymbol{\theta}}_3] \quad (2)$$

The null space bases ($\boldsymbol{\varepsilon}$) is obtained by solving J ($\bar{\boldsymbol{\theta}}$) · $\boldsymbol{\varepsilon}$ = 0.

By projecting all joint configuration deviated from averaged joint configuration ($\boldsymbol{\theta} - \bar{\boldsymbol{\theta}}$) each time point into the null-space ($\boldsymbol{\varepsilon}$) and into its orthogonal space, the components along UCM and ORT space will be identified. Sum of variance along with UCM (V_{UCM}) and perpendicular to

UCM (V_{ORT}) will be computed and normalized by the degrees of freedom (*n, d*) and the number of trials or time frames (*N*). In this case, *n* is the total number of elemental variables (three joint angles in this example) and *d* is the number of performance variables (one coordinate)

$$V_{UCM}=\frac{\sum_{j=1}^{n-d}\sum_{i=1}^{N}(\theta_{\|i}^{2})}{(n-d)*N}$$

$$V_{ORT}=\frac{\sum_{j=1}^{d}\sum_{i=1}^{N}(\theta_{\perp i}^{2})}{d*N}$$

Where $\theta_{\|\boldsymbol{i}}^{2}$ is resultant length on the space of UCM for the time frame *i* or trial *i*; $\theta_{\perp\boldsymbol{i}}^{2}$ is resultant length on the space of perpendicular to UCM for the time frame *i* or trial *i*.

Lower V_{ORT} is desirable for tasks with high consistency demanded. On the other hand, there is no standard criterion for V_{UCM}, since it does not affect the performance. If both V_{UCM} and V_{ORT} are low in certain tasks, this implies the selected elements are less variable and may be more monotonous movements. Large amount of V_{UCM}, indicates that there is a larger solution space with respect to such performance variables. The UCM approach had been used to analyze individual joint contributions to the control of the body COM (Hsu et al., 2013; Hsu et al., 2007; McCaskey et al., 2018; Scholz & Schöner, 1999).

A previous study has found that healthy young adults arranged their joint motion of foot, ankle, knee, hip-trunk, cervical, and upper cervical joints in response to support surface perturbations by returning the COM to the pre-perturbation state as higher V_{UCM} was observed, which suggested that healthy young adults used more flexible patterns of motor equivalent joint coordination to stabilize the COM (Scholz et al., 2007). The results also supported that a large solution set in the UCM allows the body to adapt to the effects of such unpredictable perturbations from the environment. Another study (Hsu et al., 2007) also examined the effect of joint configuration variance on the stability of the COM and head positions using UCM approach during quiet standing in conditions with and without vision. Both conditions showed larger V_{UCM} compared to U_{ORT}, which indicated that those joints cooperated together to control the COM and head positions. With eyes-closed, V_{UCM} is higher; however, there were no differences of U_{ORT} compared to the eyes-open condition, indicating increased joint variance had little disrupt on stabilizing the COM and head positions.

Recently, UCM has been used to investigate the effect of attentional focus on movement variability with respect to control of the leg orientation and vertical leg length during hopping in place (Fietzer et al., 2018). Unexpectedly, although both conditions showed improved consistency on landing in the same place, V_{ORT} with respect to the control of leg orientation increased in both internal and external focus conditions relative to no focus condition during takeoff, while there was no focus effect on the V_{UCM}. However, an external focus demonstrated larger V_{UCM} with respect to stabilization of leg length than internal focus during the hopping stand phase. There are several potential reasons for not seeing the expected results. First, hopping in place is a discrete task with definite start and end points. It also has a short duration which may require less range of variability adapted to the environment to achieve the goal. Second, the hopping in place task may not require a participant to control the orientation of leg during takeoff, instead, the flexibility of orientation may promote greater stability for hopping.

Summary

Attentional focus research has been burgeoning in varied areas from sports to clinical practices. In large bodies of literature, the advantage of an external focus predominates over internal focus based on the performance outcomes. In that, the constrained action hypothesis was formed to explain the mechanism, stating that external focus may allow the motor system to self-organize at a more automatic level. By utilizing of the degree of freedom of motor system effectively and flexibly, external focus may promote the flexibility and adaptability to perform proficiently in the movement. This has led researchers to suggest that an external focus may promote more “helpful” variability. However, only a few studies have explored measuring movement variability resulting from verbal instructions in-depth. Among those few studies, inadequate tasks (discrete movement), insufficient sensitivity detecting the differences, and problematic selection of performance variables have been reasonable critiques. The UCM analysis offers a promising tool to understand the structure of variability involved in multiple joints/segments affected by attentional focus. Utilizing a UCM approach to investigate the effect of attentional focus on the structure of movement variability with respect to controlling the COM while balancing is warranted.

CHAPTER III

METHODS

This chapter is divided into the following sections: participants, instruments and/or apparatus, experimental setup, data processing, data analysis, and statistical analysis.

Participants

Following a statistical power analysis using G*Power 3 (Faul et al., 2007) based on the magnitude of sway (RMSE) variable, a total of 36 healthy students (age: 21.9 ± 3.1 years; height:164.8 ± 8.3 cm; weight: 72.4 ± 11.3 kg) were recruited for this study, inclusion criteria included (a) being between the ages of 18 and 44 years, (b) having no current or recent (within last 6 months) lower extremity injuries that may affect their ability to participate in a balancing or squatting task, and (c) having a minimum of 6 months experience in strength training including the squat exercise. Exclusion criteria included answering "Yes" to any of the initial seven health screening questions found on the PAR-Q+ form (Bredin, et al., 2013). Participants unable to hold the squat position at the 45˚ knee flexion for 15 s during the screening procedure were also excluded.

Apparatus and Task

Participants in this study were asked to complete standing and squatting with 45˚ of knee flexion while balancing barefoot on two inflatable balance discs (Black Mountain Products®), which were placed on two force plates. There were two levels of difficulty in the balancing task (easy: standing on the disc for 10 s; difficult: holding squat position with knee angle at 45˚ of flexion on the discs for 10 s). For each level of difficulty, there were three different focus conditions (baseline: no instruction provided; external focus: focus on keeping the discs still; internal focus: focus on keeping the feet still). The balance discs (13 × 12 × 2 in.) were made of soft rubber and also outfitted with slip-resistant surface for the participant to stand on. For standardizing the depth of squat and eliminating extra subjective judgment of maintaining the posture, a rubber band was adjusted to the level where the participant's buttock would touch while squatting when the knee angle reaches 45˚ of flexion.

Procedures

After all potential participants were reviewed for qualifications to participate in this study, those who met all inclusion criteria were invited to sign an informed consent form. The participant was asked to change into spandex material clothing to minimize the motion artifact resulting from loose-fitting clothing. Next, the primary investigator put a total of 27 retro-reflective markers on the participant's body, and then gave a brief explanation of what the tasks were, and briefly stood on the discs as a demonstration. Participants performed three baseline trials either standing or squatting on the discs, followed by three trials while using an external focus and three trials using an internal focus.

The order of task difficulty was counterbalanced. Three baseline trials of each task difficulty were always performed first, and trials for the two focus conditions were assigned a random trial by trial order by using a sequence generator from random.org. If the sequence contained the same focus condition in the first three trials (i.e., EEEIII or IIIEEE), the randomization was conducted again to eliminate any influence of learning due to the experiment order (Wulf, Töllner, & Shea, 2007). All trials were 10 s in duration. Between each trial, a 1-minute rest period was provided. Prior to each experimental trial, a researcher assisted the participant in getting on the balance discs and read the appropriate focus instruction. Participants were asked to concentrate on the instructions and to complete the task to the best of their abilities with the arm and trunk keeping at the same position throughout both conditions.

Experimental Setup Motion Capture

A 9-camera Vicon motion capture system (Centennial, CO, USA) with a sampling rate of 250 Hz was used to capture the 3D trajectories in space of the retro-reflective markers placed on the participant's body. A total of 27 markers (Balancing marker set; see Table 2) attached on the participant's body were used to create a stick figure of the balancing motion. A static posture trial was collected prior to the balance trials and used to find the locations of a group of secondary points (see Table 3). Participants faced the direction of the positive X-axis of the global reference frame. The positive Y-axis was pointed leftward perpendicular to the X-axis. The positive Z-axis was upward. Two AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) were used to collect the COP data.

Table 2

The 39-Point (27 Markers) 'Balance' Body Model/Marker Set

Segment	Markers/Secondary points	Description
Head	Markers (4)	Anterior head
		Right head
		Left head
		Top head
	Secondary (1)	Mid-head (mid-point of right and left head)
Thorax	Markers (2)	Spinous process of seventh cervical vertebra (C7)
		Sternal notch (SN)
	Secondary (1)	Mid-shoulder (mid-point of C7 and SN)

Abdomen	Secondary (1)	L4/L5 (computed using the 'MacKinnon Method') (see Table 4)
pelvis	Markers (7)	Right and left greater trochanters (GTs) Right and left anterior superior iliac spines (ASISs) Right and left posterior superior iliac spines (PSISs) Sacrum
	Secondary (3)	mid-ASIS (mid-point of right and left ASISs) mid-RPelvis (mid-point of right ASIS and PSIS) mid-LPelvis (mid-point of left ASIS and PSIS)
Thighs	Markers (3 × 2)	Right and left lateral thigh Right and left lateral femoral epicondyle Right and left medial femoral epicondyle
	Secondary (2 × 2)	Right and left hip joints (calculated using the 'Tylkowski-Andriacchi method (Bell et al., 1990). (see Table 4) Right and left knee joints (mid-point of lateral and medial femoral epicondyle)
Shanks	Markers (2 × 2)	Right and left lateral malleoli Right and left medial malleoli
	Secondary (1 × 2)	Right and left ankle joints (mid-point of lateral and medial malleoli)
Feet	Markers (2 × 2)	Right and left heels Right and left toes.

Table 3

Methods Used in Locating the Computed Joints

Joint	Method	Description
Hip center	Tylkowski-Andriacchi	In the static posture trial, the hip joint center will be computed based on Right ASIS left ASIS, sacrum, and GT markers (Bell et al., 1990).
L4/L5	MacKinnon	In the static posture trial, based on the right and left ASISs and mid-PSIS) (Mackinnon & Winter, 1993).

Data Reduction

The captured balancing motions and COP data were initially processed on Vicon Nexus to generate the C3D-format data. The C3D files were then imported into Kwon3D Motion Analysis Suite (Version XP; Visol, Seoul, Korea) for subsequent processing and analysis. The marker and COP coordinates were digitally filtered using a Butterworth 4th-order zero phase lag low-pass filter with an appropriate cutoff frequency determined by the residual plot from Kwon3D Motion Analysis Suite.

In the balancing model, 10 segments (see Table 3) were defined. Thirteen additional points (including seven joint centers) were computed based on the marker coordinates. Zatsiorsky and Seluyanov's body segment parameters (ratios) corrected by De Leva (1996) were used in locating the COM of the segments.

Local Coordinate System

The segmental reference frame definitions, proximal-distal relationships among the segments, and the rotation sequences reported by Kwon et al. (2013) were used to compute the orientation angles. Ten reference frames (pelvis, abdomen, thorax, head, both thighs, both shanks, both feet) were defined (see Table 5). The X-, Y-, and Z-axis of each segment were aligned with the mediolateral, anteroposterior, and longitudinal axes of each segment, respectively. To define the local reference frames, an anatomical plane was first defined using two axes (first axis and temporary second axis). Then the third axis was the cross product of the first and temporary second axis unit vectors. The true second axis was lastly defined as the cross product of the first and third axis unit vectors.

Table 4

Definitions of Local Reference Frames of Each Segment

Segment	Primary axis	Temporary second axis	Plane
Head	Mid-shoulder to Mid-head (+Z axis)	L Head marker to R Head marker (+X axis)	Frontal
Thorax	L4/L5 to Mid-Shoulder (+Z axis)	C7 marker to SN marker (+Y axis)	Sagittal
Abdomen	Mid Pelvis to L4/L5 (+Z axis)	Mid- L Pelvis to mid- R pelvis (+X axis)	Frontal
Pelvis	L Hip joint to R Hip joint (+X axis)	Mid Hip to Mid Pelvis (+Z axis)	Frontal
R Thigh	R Knee joint to R Hip joint (+Z axis)	R Hip Joint to R thigh marker (+X axis)	Frontal
L Thigh	L Knee joint to L Hip joint (+Z axis)	L thigh marker to L Hip joint (+X axis)	Frontal
R Shank	R Ankle joint to R Knee joint (+Z axis)	R medial malleoli marker to R lateral malleoli marker (+X axis)	Frontal

L Shank	L Ankle joint to L Knee joint (+Z axis)	L lateral malleoli marker to L medial malleoli marker (+X axis)	Frontal
R Foot	R toe marker to R heel marker (+Z axis)	R heel marker to R Ankle joint (+Y axis)	Sagittal
L Foot	L toe marker to L heel marker (+Z axis)	L heel marker to L Ankle joint (+Y axis)	Sagittal

Abbreviations. R (right), L (left)

An XYZ (mediolateral-anteroposterior-longitudinal) rotation sequence was used for computing the relative orientation angles of the segments to their respective linked proximal segments. By using the transformation matrices based on the global coordinates of the markers, the unit coordinate vectors of the distal and proximal segmental reference frames form the transformation matrices from the global frame are as follows:

$$T_{P/G} = \begin{bmatrix} \mathbf{i}_P \\ \mathbf{j}_P \\ \mathbf{k}_P \end{bmatrix} = \begin{bmatrix} t_{11P} & t_{12P} & t_{13P} \\ t_{21P} & t_{22P} & t_{23P} \\ t_{31P} & t_{32P} & t_{33P} \end{bmatrix} \quad (3)$$

$$T_{D/G} = \begin{bmatrix} \mathbf{i}_D \\ \mathbf{j}_D \\ \mathbf{k}_D \end{bmatrix} = \begin{bmatrix} t_{11D} & t_{12D} & t_{13D} \\ t_{21D} & t_{22D} & t_{23D} \\ t_{31D} & t_{32D} & t_{33D} \end{bmatrix} \quad (4)$$

where, **i**, **j**, and **k** are the axis unit vectors of the segmental reference frame, and $\boldsymbol{t}_{11} – \boldsymbol{t}_{33}$ are the components of the axis unit vectors (three for each axis). *P* is the proximal segment, *D* is the distal segment, and *G* is the global reference frame. The transformation matrix from the proximal reference frame (frame P) to the distal reference frame (frame D) was computed from the transformation matrices as the following equation:

$$\mathbf{T}_{D/P} = \mathbf{T}_{D/G}\mathbf{T}_{G/P} = \mathbf{T}_{D/G}\,\mathbf{T}'_{P/G} \tag{5}$$

where $\mathbf{T}_{D/P}$ is the relative orientation matrix of distal segment frame to proximal segment frame, and $\mathbf{T}'_{P/G}$ is the transpose of $\mathbf{T}_{P/G}$. Relative orientation angles of the segments to their proximal segments were computed from relative orientation matrices based on X-Y-Z rotation sequence:

$$\mathbf{T}_{D/P} = \begin{bmatrix} \cos\theta_2 \cos\theta_3 & \sin\theta_1 \sin\theta_2 \cos\theta_3 + \cos\theta_1 \ \sin\theta_3 & -\cos\theta_1 \sin\theta_2 \cos\theta_3 + \sin\theta_1 \ \sin\theta_3 \\ -\cos\theta_2 \cos\theta_3 & -\sin\theta_1 \sin\theta_2 \cos\theta_3 + \cos\theta_1 \ \sin\theta_3 & \cos\theta_1 \sin\theta_2 \cos\theta_3 + \sin\theta_1 \ \sin\theta_3 \\ \sin\theta_1 & -\sin\theta_1 \cos\theta_2 & \sin\theta_1 \sin\theta_2 \end{bmatrix} \tag{6}$$

$\theta 1$, $\theta 2$, and $\theta 3$ were the relative orientation angles of the distal segment to the proximal segment.

Uncontrolled Manifold (UCM) Analysis

Joint angles and center of mass excursion

The coordinates of joints location (mid-head, mid-shoulder, L4/L5, hip joint, knee joint, ankle joint, and toe marker) retracted from the Kwon3D Motion Analysis were used to calculate the joint angles of the foot ($\boldsymbol{\theta}_F$), ankle ($\boldsymbol{\theta}_A$), knee ($\boldsymbol{\theta}_K$), hip ($\boldsymbol{\theta}_H$), lumbar ($\boldsymbol{\theta}_L$), and neck ($\boldsymbol{\theta}_N$) in sagittal plane. The angles measured in the clockwise direction hold negative values (i.e., ankle, hip, and neck; see Figure 3). Whole-body COM position in the sagittal plane was calculated as the weighted sum of the assumedly symmetric seven-segment mode (feet, shanks, thighs, pelvis, abdominal, thorax and head). Based on estimated segmental COM and mass proportions, the instantaneous position of the body's COM was computed for every frame (Winter et al., 1990). The geometrical model relating the COM to the joint configuration with origin at the toe was expressed through a trigonometric analysis (7):

$$\mathrm{COM_X} =$$

$$2M_{\mathrm{F}}[d_{\mathrm{F}}l_{\mathrm{F}}\cos(\boldsymbol{\theta}_{\mathrm{F}})] +$$

$$2M_{\mathrm{S}}[l_{\mathrm{F}}\cos(\boldsymbol{\theta}_{\mathrm{F}}) + d_{\mathrm{S}}l_{\mathrm{S}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}})] +$$

$$2M_{\mathrm{T}}[l_{\mathrm{F}}\cos(\boldsymbol{\theta}_{\mathrm{F}}) + l_{\mathrm{S}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}}) + d_{\mathrm{T}}l_{\mathrm{T}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}})] +$$

$$M_{\mathrm{A}}[l_{\mathrm{F}}\cos(\boldsymbol{\theta}_{\mathrm{F}}) + l_{\mathrm{S}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}}) + l_{\mathrm{T}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}}) + d_{\mathrm{A}}l_{\mathrm{A}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}} + \boldsymbol{\theta}_{\mathrm{H}})] +$$

$$M_{\mathrm{TH}}[l_{\mathrm{F}}\cos(\boldsymbol{\theta}_{\mathrm{F}}) + l_{\mathrm{S}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}}) + l_{\mathrm{T}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}}) + l_{\mathrm{A}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}} + \boldsymbol{\theta}_{\mathrm{H}})$$
$$+ d_{\mathrm{TR}}l_{\mathrm{TR}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}} + \boldsymbol{\theta}_{\mathrm{H}} + \boldsymbol{\theta}_{\mathrm{L}})] +$$

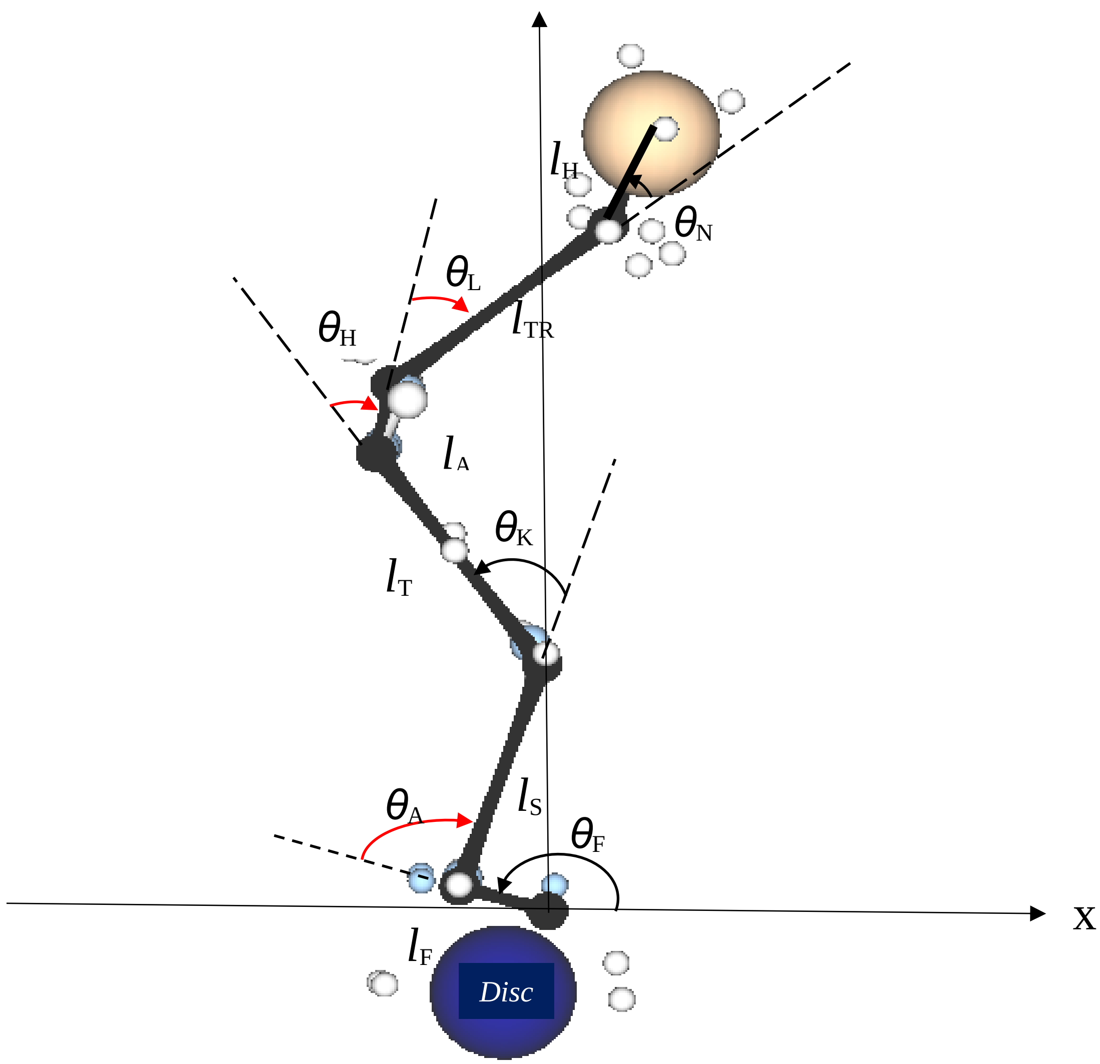
$$M_{\mathrm{H}}[l_{\mathrm{F}}\cos(\boldsymbol{\theta}_{\mathrm{F}}) + l_{\mathrm{S}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}}) + l_{\mathrm{T}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}}) + l_{\mathrm{A}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}} + \boldsymbol{\theta}_{\mathrm{H}}) +$$
$$l_{\mathrm{TR}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}} + \boldsymbol{\theta}_{\mathrm{H}} + \boldsymbol{\theta}_{\mathrm{L}}) + d_{\mathrm{H}}l_{\mathrm{H}}\cos(\boldsymbol{\theta}_{\mathrm{F}} + \boldsymbol{\theta}_{\mathrm{A}} + \boldsymbol{\theta}_{\mathrm{K}} + \boldsymbol{\theta}_{\mathrm{H}} + \boldsymbol{\theta}_{\mathrm{L}} + \boldsymbol{\theta}_{\mathrm{N}})]$$

(7)

where $\boldsymbol{\theta}_{\mathrm{A}}, \ldots, \boldsymbol{\theta}_{\mathrm{N}}$ are the calculated joint angles; $l_{\mathrm{F}}, \ldots, l_{\mathrm{H}}$ are the segment's length calculated from the static calibration trial; $d_{\mathrm{F}}, \ldots, d_{\mathrm{H}}$ are the percentages of the segment lengths from the distal end to the COM of the segment; and $M_{\mathrm{T}}, \ldots, M_{\mathrm{H}}$ are the proportion of total body mass for each segment respectively.

Figure 3

Geometric model



$\boldsymbol{\theta}_F$: Foot angle; $\boldsymbol{\theta}_A$: Ankle angle; $\boldsymbol{\theta}_H$: Hip angle; $\boldsymbol{\theta}_K$: Knee angle; $\boldsymbol{\theta}_L$: Lumbar angle; $\boldsymbol{\theta}_N$: Neck angle; $\boldsymbol{l}_{F:}$ Foot length; $\boldsymbol{l}_{S:}$ Shank length; $\boldsymbol{l}_{T:}$ Thigh length; $\boldsymbol{l}_A$: Abdomen length; $\boldsymbol{l}_{TR}$: Truck length; $\boldsymbol{l}_H$: Head length.

Computation of joint angle variability

In this study, our interest was understanding how attentional focus influences the coordination of the joints (elemental variables, i.e., $\boldsymbol{\theta}_F$, $\boldsymbol{\theta}_A$, $\boldsymbol{\theta}_K$, $\boldsymbol{\theta}_H$, $\boldsymbol{\theta}_L$, $\boldsymbol{\theta}_N$) affecting the COM position (the performance variable) during a balancing task. The measure of multi-segmental COM control was evaluated at each time frame to analyze the postural responses during the balancing task. The variance of the control variables (joint angles) from every frame of each trial (a total of 2,500 frames for each trial) across the attempts can be partitioned into two components: parallel and orthogonal to the UCM (V_{UCM} and V_{ORT}, respectively). Those two components quantify the amount of variability affecting unwanted change (nongoal-equivalent) and the amount of variability maintaining the COM to its balanced position (goal-equivalent). The following steps are for obtaining the variance of both components:

1. Set the reference joint configuration $[\bar{\boldsymbol{\theta}}]$, which is the mean joint configuration of the foot, ankle, knee, hip, lumbar, and neck joint angle ($\bar{\theta}_F$, $\bar{\theta}_A$, $\bar{\theta}_K$, $\bar{\theta}_H$,$\bar{\theta}_L$, $\bar{\theta}_N$) during the 10 s of the balancing task for each trial.

$$[\bar{\boldsymbol{\theta}}] = \begin{bmatrix} \bar{\theta}_F \\ \bar{\theta}_A \\ \bar{\theta}_K \\ \bar{\theta}_H \\ \bar{\theta}_L \\ \bar{\theta}_N \end{bmatrix}$$

2. Compute the joint deviation vector $[\boldsymbol{\theta} - \bar{\boldsymbol{\theta}}]_i$ which the difference between the current joint configuration at each time frame(i) in the trial and the reference joint configuration.

$$[\boldsymbol{\theta} - \overline{\boldsymbol{\theta}}]_i = \begin{bmatrix} \boldsymbol{\theta}_{i\mathrm{F}} - \bar{\theta}_{\mathrm{F}} \\ \boldsymbol{\theta}_{i\mathrm{A}} - \bar{\theta}_{\mathrm{A}} \\ \boldsymbol{\theta}_{i\mathrm{K}} - \bar{\theta}_{\mathrm{K}} \\ \boldsymbol{\theta}_{i\mathrm{H}} - \bar{\theta}_{\mathrm{H}} \\ \boldsymbol{\theta}_{i\mathrm{L}} - \bar{\theta}_{\mathrm{L}} \\ \boldsymbol{\theta}_{i\mathrm{N}} - \bar{\theta}_{\mathrm{N}} \end{bmatrix}$$

3. Build the Jacobian matrix (*J*), which relates changes in COM position to changes in joint configuration from the geometrical model.

$$J = \begin{bmatrix} \frac{\partial COMx}{\partial \theta_{\mathrm{F}}} & \frac{\partial COMx}{\partial \theta_{\mathrm{A}}} & \frac{\partial COMx}{\partial \theta_{\mathrm{K}}} & \frac{\partial COMx}{\partial \theta_{\mathrm{H}}} & \frac{\partial COMx}{\partial \theta_{\mathrm{L}}} & \frac{\partial COMx}{\partial \theta_{\mathrm{N}}} \end{bmatrix}$$

4. Compute the null-space of the Jacobian matrix ($\boldsymbol{\varepsilon}$) based on the reference joint configuration ($\overline{\boldsymbol{\theta}}$)

$$\text{where } 0 = J(\overline{\boldsymbol{\theta}}) \cdot \boldsymbol{\varepsilon}$$

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{1F} & \varepsilon_{2F} & \varepsilon_{3F} & \varepsilon_{4F} & \varepsilon_{5F} \\ \varepsilon_{1A} & \varepsilon_{2A} & \varepsilon_{3A} & \varepsilon_{4A} & \varepsilon_{5A} \\ \varepsilon_{1K} & \varepsilon_{2K} & \varepsilon_{3K} & \varepsilon_{4K} & \varepsilon_{5K} \\ \varepsilon_{1H} & \varepsilon_{2H} & \varepsilon_{3H} & \varepsilon_{4H} & \varepsilon_{5H} \\ \varepsilon_{1L} & \varepsilon_{2L} & \varepsilon_{3L} & \varepsilon_{4L} & \varepsilon_{5L} \\ \varepsilon_{1N} & \varepsilon_{2N} & \varepsilon_{3N} & \varepsilon_{4N} & \varepsilon_{5N} \end{bmatrix}$$

where $\boldsymbol{\varepsilon}$ is 6×5 matrix which consists with the basis vectors of the null space which represent the linear subspace of all joint-configurations that stabilize the COM position.

5. Decompose all joint deviation vectors $[\boldsymbol{\theta} - \overline{\boldsymbol{\theta}}]_i$ by projecting them into the null-space and into its orthogonal space.

$$\boldsymbol{\theta}_{\|\boldsymbol{i}} = [\boldsymbol{\theta} - \overline{\boldsymbol{\theta}}]'_{i} \cdot \boldsymbol{\varepsilon}$$

$$\boldsymbol{\theta}_{\perp \boldsymbol{i}} = [\boldsymbol{\theta} - \overline{\boldsymbol{\theta}}]_{i} - \boldsymbol{\theta}_{\|}$$

where $\boldsymbol{\theta}_{\|\boldsymbol{i}}$ is the vector of joint configuration for each time point projected to the null-space of Jacobian ($\boldsymbol{\varepsilon}$), and $\boldsymbol{\theta}_{\perp \boldsymbol{i}}$ is the vector of joint configuration for each time point projected orthogonal to the null-space of Jacobian.

6. Compute resultant length and normalize each projection based on the degrees of freedom

$$V_{UCM} = \frac{\sum_{j=1}^{n-d} \sum_{i=1}^{N} (\theta_{\| i}^{2})}{(n-d) * N}$$

$$V_{ORT} = \frac{\sum_{j=1}^{d} \sum_{i=1}^{N} (\theta_{\perp i}^{2})}{d * N}$$

where V_{UCM} is variance within the UCM, and V_{ORT} is variance in the joint space orthogonal to the UCM. *N* is the number of recorded frames for each trial, *n* is the total number of joints (six joints in this study), and *d* is the number of special dimensions of COM (i.e., one dimension in the sagittal plane).

Center of Pressure

The combined COP coordinates from the two force plates were imported to MATLAB (Mathworks Inc.,Version 2016a). The *SD* of X (mediolateral), Y (anteroposterior) direction COP trace, and 95% confidence-ellipse area (Schubert & Kirchner, 2014) during 10 s of each trial were calculated by the customized MATLAB code.

Dependent Variables and Statistical Analysis

The *SD* of X and Y COP trajectory (COP_X, COP_Y) and the 95% confidence-ellipse area ($EA_{95\%}$) were mainly used to determine the magnitude of error during the balancing task performance. For the assessment of movement variability, there were two categories of variables. First were the *SD* of ankle, knee, hip, L4/L5, and C7 orientation angle in the sagittal plane. Second were the variance within the UCM (V_{UCM}), and variance in the joint space orthogonal to the UCM (V_{ORT}). All dependent variables were averaged across the three trials for each condition. Each group of variables (COP trace, *SD* of joint angles, and UCM) was analyzed in separate repeated measures factorial MANOVAs to assess differences due to focus conditions (internal, external, baseline) and levels of difficulty (easy, difficult) as well as the interaction effect for attention focus modulated by level of difficulty. Significant effects in the MANOVAs were followed up with univariate tests for each dependent variable, and Sidak *post-hoc* tests were used for pairwise comparisons between focus conditions. The alpha level for all analyses was set at .05. All statistical tests were conducted in IBM SPSS Statistics (version 24; IBMCorp., Armonk, NY).

CHAPTER IV

RESULTS

The purpose of the study was to investigate the effects of attentional focus (external and internal focus) and the level of task difficulty on balance performance (COP trajectory) as well as movement variability (*SD* of joint angles, V_{UCM}, V_{ORT}) during a task involving standing and squatting on inflatable balancing discs. The data presented within this chapter are organized into three sections: (a) COP trajectory; (b) *SD* of orientation angles in the sagittal plane; (c) variance in the joint space (V_{UCM} and V_{ORT}), and (d) manipulation check

COP Trajectory

Ninety-five percent confidence-ellipse area, COP_X and COP_Y values in each focus condition are displayed in Table 5. A 2 (difficulty) × 3 (focus condition) MANOVA was conducted with the 3 measures of balance performance (95% confidence-ellipse area, COP_X and COP_Y). There was a main effect of focus condition, $\Lambda_{Wilk's} = .346$, $F(6,30) = 9.67$, $p < .001$, $\eta_p^2 = .654$, as well as a main effect of difficulty, $\Lambda_{Wilk's} = .734$, $F(6,30) = 3.991$, $p = .016$, $\eta_p^2 = .266$. There was no difficulty x focus interaction, $\Lambda_{Wilk's} = .738$, $F(3,33) = 1.776$, $p = .138$, $\eta_p^2 = .262$.

Univariate tests were used to follow-up significant effects in the MANOVA. For 95% confidence-ellipse area ($mEA_{95\%}$), the univariate F test showed that there was a main effect of focus condition, $F(2,70) = 13.038$, $p < .001$, $\eta_p^2 = .271$. Pairwise comparisons revealed that 95% confidence-ellipse area in both external and internal focus conditions was significantly lower than baseline ($p < .001$, $p = .029$, respectively), whereas there were no differences between external and internal focus conditions ($p = .192$). There was no main effect of difficulty, $F(2,70) = .520$, p

= .476, η_p^2 = .015, and the difficulty x focus interaction was not significant, $F(2,70) = 2.942$, $p = .059$, $\eta_p^2 = .078$.

Regarding the *SD* of COP in the anterior/posterior direction (COP_X), univariate analyses revealed that there were main effects of difficulty, $F(1,35) = 8.790$, $p = .005$, $\eta_p^2 = .201$, and focus condition, $F(2,70) = 14.771$, $p < .001$, $\eta_p^2 = .297$. There was no significant difficulty x focus interaction, $F(2,70) = 2.214$, $p = .117$, $\eta_p^2 = .060$. Pairwise comparisons showed that in the easier version of the task (upright stance on the discs) the COP_X was significantly larger than the difficult task (45º squat stance on the discs; $p = .005$). Across both levels of difficulty, COP_X was significantly lower in the external focus condition compared to the internal focus condition and baseline ($p = .024$, $p < .001$, respectively). There were no significant differences between the internal focus condition and baseline ($p = .085$).

In terms of the *SD* of the COP in the medial/lateral direction (COP_Y), the univariate analysis showed that there was a significant main effect of focus condition $F(2,70) = 4.708$, $p = .012$, $\eta_p^2 = .119$. Pairwise comparisons showed that COP_Y was significantly lower in the external focus condition compared to baseline ($p = .013$). There were no significant differences between the external and internal focus condition ($p = .517$), nor between internal and baseline ($p = .226$). There was no main effect of difficulty, $F(1,35) = 2.346$, $p = .135$, $\eta_p^2 = .063$. The interaction between difficulty and focus condition was also non-significant $F(2,70) = 2.373$, $p = .101$, $\eta_p^2 = .063$).

Table 5

Comparison of the Center of Pressure Trajectory

Condition / Variables	Easy			Difficult			Summary
	B	EF	IF	B	EF	IF	
Area (cm²)	18.52 ± 6.81	13.49 ± 5.96	14.49 ± 6.58	16.12 ± 6.12	13.47 ± 5.80	15.46 ± 7.48	Main effect: EF (13.48±0.87) < B (17.32±0.94) & IF (14.97±1.01)
COP_X (cm)	1.25 ± 0.30	1.06 ± 0.25	1.12 ± 0.27	1.10 ± 0.25	0..98 ± 0.22	1.09 ± 0.28	Main effect: EF (1.02±0.03) < B (1.18±0.04) & IF (1.11±0.04); Difficult (1.06±0.04) < Easy (1.14±0.04)
COP_Y (cm)	0.80 ± 0.20	0.67 ± 0.20	0.72 ± 0.18	0.79 ± 0.19	0.76 ± 0.25	0.77 ± 0.22	Main effect: EF (0.71±0.03) < B (0.79±0.03)

Abbreviations: B, baseline; EF, external focus; IF, internal focus; COP_X and COP_Y, standard deviation of X and Y COP trajectory

Standard Deviation of Orientation Angles in the Sagittal Plane

The *SD* of orientation angles in the sagittal plane for each focus condition are displayed in Table 6. A 2 (difficulty) × 3 (focus condition) MANOVA was conducted with the SD of orientation angles at five different joints (Ankle, Knee, Hip, L4/L5, and C7). There was an interaction between difficulty and focus condition, $\Lambda_{Wilk's} = .471$, $F(10,26) = 2.317$, $p = .042$, $\eta_p^2 = .271$. Main effects of difficulty, $\Lambda_{Wilk's} = .457$, $F(5,31) = 7.376$, $p < .001$, $\eta_p^2 = .543$, and focus condition, $\Lambda_{Wilk's} = .389$, $F(10,26) = 4.081$, $p = .002$, $\eta_p^2 = .611$ were also significant.

For the ankle joint, a univariate analysis revealed that there were main effects of difficulty, $F(1,35) = 13.721$, $p = .001$, $\eta_p^2 = .282$, and focus condition, $F(2,70) = 5.943$, $p = .004$, $\eta_p^2 = .145$, as well as a significant difficulty x focus interaction, $F(2,70) = 3.464$, $p = .037$, $\eta_p^2 = .090$. Pairwise comparisons showed that in the easier version of the task (upright stance on the discs) the *SD* of ankle orientation angle in the external focus condition was significantly lower than baseline ($p = .003$) whereas there were no differences between the external and internal focus conditions ($p > .517$), nor the internal focus and baseline conditions ($p = .164$). For the difficult task (45º squat stance on the discs), there were no differences among three focus conditions (*ps* > .05).

In terms of *SD* of knee orientation angle, univariate analyses revealed no significant difficulty x focus condition interaction, $F(1.622,56.781) = 1.342$, $p = .266$, $\eta_p^2 = .037$. There was a main effect of difficulty, $F(1,35) = 10.448$, $p = .003$, $\eta_p^2 = .230$, with the *SD* of knee orientation angle in the difficult task (45º squat stance on the discs) being significantly larger than in the easier version of the task (upright stance on the discs). A focus condition main effect was also significant, $F(1.661,58.150) = 3.700$, $p = .038$, $\eta_p^2 = .096$. Pairwise comparisons revealed that the external focus condition exhibited smaller *SD* than the baseline ($p = .050$) but not the internal focus condition ($p = .382$). Internal focus and baseline conditions did not differ ($p = .420$).

Regarding *SD* of hip orientation angle, univariate analyses revealed that there were no difficulty x focus condition interaction, $F(2,32) = 1.483$, $p = .234$, $\eta_p^2 = .041$, and no main effect of difficulty, $F(1,35) = 2.816$, $p = .102$, $\eta_p^2 = .075$. There was a main effect of focus condition, $F(2,70) = 6.267$, $p = .003$, $\eta_p^2 = .152$. Pairwise comparisons showed that the external focus condition exhibited smaller *SD* than the baseline ($p = .003$) but not the internal focus condition ($p = .824$). Internal focus and baseline conditions did not differ ($p = .066$).

As for L4/L5, no significant main effects or interactions were detected (*p*s > .05). However, the *SD* of C7 orientation angles displayed a difficulty main effect, $F(1,35) = 10.784$, $p = .002$, $\eta_p^2 = .236$), where pairwise comparisons indicated that *SD* of C7 orientation angles was smaller in the difficult task than in the easier task.

Table 6

Comparison of the SD of orientation angles in the sagittal plane

Variables \ Condition	Easy			Difficult			Summary
	B	EF	IF	B	EF	IF	
Ankle	2.97 ± 0.79	2.55 ± 0.72 [a]	2.70 ± 0.64	2.36 ± 0.67	2.28 ± 0.71	2.52 ± 0.93	Difficulty x focus interaction: Easy: EF < B
Knee	1.08 ± 0.45	1.01 ± 0.58	1.06 ± 0.59	1.45 ± 0.72	1.19 ± 0.48	1.28 ± 0.49	Main effect: EF (1.10±0.08) < B (1.27±0.08) Difficult (1.31±0.08) > Easy (1.05±0.07)
Hip	1.21 ± 0.49	1.09 ± 0.54	1.04 ± 0.58	1.37 ± 0.56	1.09 ± 0.43	1.22 ± 0.40	Main effect: EF (1.01±0.07) < B (1.29±0.07)
L4/L5	1.35 ± 0.52	1.19 ± 0.43	1.28 ± 0.53	1.22 ± 0.54	1.19 ± 0.49	1.37 ± 0.96	None
C7	0.56 ± 0.41	0.48 ± 0.21	0.51 ± 0.28	0.45 ± 0.25	0.40 ± 0.17	0.47 ± 0.25	Main effect: Difficult (0.44±0.03) < Easy (0.51±0.04)

Abbreviations: B, baseline; EF, external focus; IF, internal focus; F; [a] significantly ($p < 0.016$) different from the matching baseline condition

Variance in the Joint Space (V_{UCM} ,V_{ORT})

V_{UCM} and V_{ORT} values in each focus condition are displayed in Table 7 and Figure 4. A 2 (difficulty) × 3 (focus condition) MANOVA was conducted with the 2 measures of variance in the joint space (V_{UCM} ,V_{ORT}). There was a main effect of focus condition, $\Lambda_{Wilk's} = .699$, $F(4,32) = 3.446$, $p = .019$, $\eta_p^2 = .301$. but no main effect of difficulty, $\Lambda_{Wilk's} = .946$, $F(2,34) = .967$, $p = .391$, $\eta_p^2 = .054$, nor a difficulty x focus interaction, $\Lambda_{Wilk's} = .865$, $F(4,32) = 1.244$, $p = .312$, $\eta_p^2 = .135$.

For V_{UCM}, a univariate F test showed that there was a main effect of focus condition, $F(1.58,55.19) = 4.280$, $p = .026$, $\eta_p^2 = .109$, but no main effect of difficulty, $F(1,35) = .019$, $p = .891$, $\eta_p^2 = .001$. No difficulty × focus condition interaction was observed, $F(1.40, 48.85) = 3.274$, $p = .063$, $\eta_p^2 = .086$). Pairwise comparisons revealed that V_{UCM} was lower in the external focus condition ($p = .009$) than in baseline, whereas there were no differences between external and internal focus ($p =.073$). The differences between internal and baseline were also non-significant ($p =.954$).

Regarding V_{ORT}, a univariate analysis revealed that there were neither main effects of difficulty, $F(1,35) = 1.162$, $p = .288$, $\eta_p^2 = .032$, nor focus condition, $F(1.55, 54.10) = 2.312$, $p = .121$, $\eta_p^2 = .062$. No difficulty x focus interaction was observed, $F(1.41, 49.26) = .599$, $p = .497$, $\eta_p^2 =.017$.

Table 7

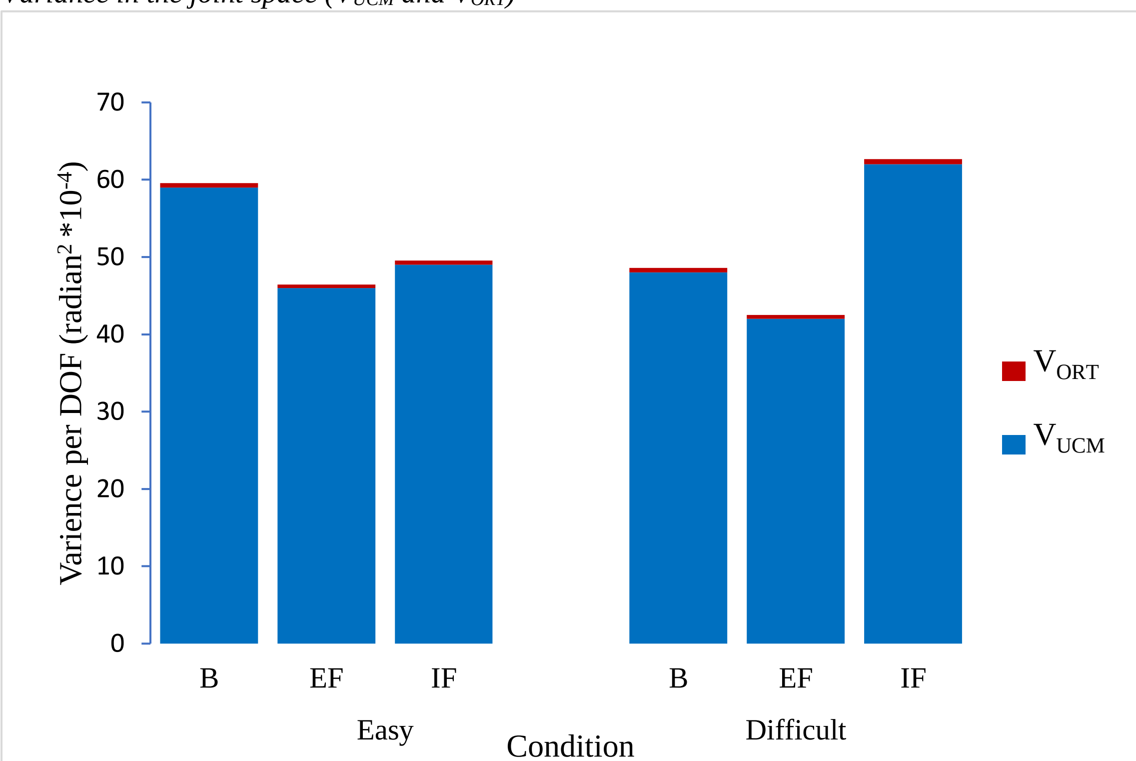
Comparison of variance in the joint space (V_{UCM} and V_{ORT})

Variables \ Condition	Easy			Difficult			Summary
	B	EF	IF	B	EF	IF	
UCM #	0.59 ± 0.36	0.46 ± 0.38	0.49 ± 0.39	0.48 ± 0.32	0.42 ± 0.31	0.62 ± 0.65	Main effect: EF (0.44±0.05) < B (0.53±0.05)
ORT ^	0.57 ± 0.49	0.45 ± 0.42	0.54 ± 0.66	0.58 ± 0.42	0.52 ± 0.40	0.67 ± 0.61	None

Abbreviations: B, baseline; EF, external focus; IF, internal focus; F; # units are radian^2 *10^{-2}; ^ units are radian^2 *10^{-4}

Figure 4

Variance in the joint space (V_{UCM} and V_{ORT})



B, baseline; EF, external focus; IF, internal focus

CHAPTER V

DISCUSSION

This study investigated the effects of attentional focus and the level of task difficulty on movement variability as well as balance performance during a task involving standing and squatting on inflatable balancing discs. Balance performance was quantified by measuring the standard deviation of the COP trajectory in the anterior-posterior (COP_X) and medial-lateral (COP_Y) directions, and the 95% confidence-ellipse area ($EA_{95\%}$) across the three attentional focus conditions and two task difficulties. For a better understanding of the underlying causes of attentional focus effects on performance and the possible mechanism of the constrained action hypothesis, the individual joint variability across the movement represented by *SD* of orientation angles, and structural variances among the joints indexed by V_{UCM} and V_{ORT} were calculated to determine how the movement variability reacted due to the different attentional focus conditions and task difficulties. It was anticipated that for the more difficult squatting version of the task, the *SD* of COP_X and COP_Y as well as $EA_{95\%}$ would be smaller, the *SD* of joint angles would be larger, the V_{UCM} would be higher and V_{ORT} would be lower in an external focus compared with an internal focus. Differences between the two focus conditions when standing upright on the inflatable balancing discs were not expected.

The Effect of Attentional Focus and Task Difficulty on Balance Performance

One purpose of this study was to examine whether changes in task difficulty would influence the effect of attentional focus. The reduced magnitude of error while using an external focus in balancing tasks has been replicated several times (McNevin et al., 2003; Wulf et al., 1998; Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001), but there have also been studies reporting no benefit of external focus, which may result from relative difficulties of the task (Wulf, 2008; Wulf, Töllner, & Shea, 2007). Pilot data from our lab revealed no significant differences between focus conditions while balancing on the discs with a standing posture. It is reasonable to assume that if difficulty is too low, relatively automatic performance could be possible regardless of attentional focus. In the present study, the more challenging balancing task required more forceful muscle contractions to counterbalance the increased lever arm of joints in the squat position compared to the standing position. It was anticipated that the magnitude of error would be smaller in an external focus than in an internal focus in the difficult condition (balancing in a squatting position on inflatable balancing discs). In the easy condition (standing upright on inflatable balancing discs), no differences between the two focus conditions were expected.

For the balance performance in this study, the task difficulty did not influence the effect of attentional focus, unexpectedly. The *SD* of COPx was smaller in an external focus condition compared to an internal focus condition across both levels of difficulty. The pilot study was similarly powered, used the same easier version of task, and did not observe the effect of attentional focus. A potential difference between the studies may relate to the time length of the trial. The trial in the pilot study was 20 s in duration, whereas, the one in current study was only 10 s, which may have made it easier for participants to maintain focus on the assigned instruction throughout the whole trial.

Although the findings from the present study were theoretically contradictory to a previous study demonstrating that relative task difficulty influenced the presence of the attentional focus effect (Wulf, Töllner, & Shea, 2007), the pattern of results was consistent with their findings with the same task. In their study, Wulf, Töllner, & Shea (2007) showed that while standing on a rubber disc in a single-leg or double-leg stance, the RMSE of COP trajectory was lower with an external relative to an internal focus. However, no significant differences between focus conditions were observed during quiet standing on a solid and foam surface. In the current study, differences were observed between the two focus conditions across both versions of task, where the easier version standing on two inflatable discs was similar to the double-leg standing on a single inflatable disc in the previous experiment (Wulf, Töllner, & Shea, 2007). One possibility is that, double-leg standing and holding in a squatting position on the inflatable discs may create a sufficient challenge to yield performance differences as a result of the type of attentional focus in both standing and squatting postures.

It should be noticed that only *SD* of COPx showed differences between external and internal focus conditions. One reason could be that the movement in this balancing task is similar to standing which mainly occurs in the sagittal plane, resulting in higher *SD* of COP in the anteroposterior direction (O'Connor & Kuo, 2009). Therefore, it is rational to expect fewer chances to detect changes in the mediolateral (Y) direction. There was a trend of decreasing 95% confidence-ellipse area in external focus relative to internal focus condition although it did not reach a significant level. In previous studies, 95% confidence-ellipse area was an applicable assessment tool of balance performance (Alahmari et al., 2014; Duarte, 2015; Schubert & Kirchner, 2014). However, the calculation of 95% confidence-ellipse area may correlated to both *SD* of COPx and $COP_{Y,}$ and it appeared in this study the effect of attentional focus occurred primarily in the anterior-posterior direction.

The Effect of Attentional Focus and Task Difficulty on Standard Deviation of Orientation Angles in the Sagittal Plane

Traditionally, the variability in movement strategies has been quantified by measuring the standard deviation of various joint angles which are all based on a single statistic. There were several studies using the standard deviation to identify the degrees of freedom that are frozen out in early stage of learning and subsequently released over practice (Caillou et al., 2002; Vereijken et al., 1992). According to previous studies, the variability measurements such as *SD* could differentiate the effect of varied attentional focus conditions as well (Lohse et al., 2014; Lohse et al., 2010). Based on this prior literature, it was hypothesized that the *SD* of joint angles (ankle, knee, hip, L4/L5, C7 orientation angle in the sagittal plane) would be larger in an external focus than in an internal focus when balancing in a more challenging task, whereas no differences between the focus conditions were expected when balancing in the easier task.

The results revealed that there was actually less variability in ankle movement in the sagittal plane (dorsi/plantar flexion) while adopting an external focus compared to baseline in the easier version of task. For the hip and knee flexion/extension angles, they showed a similar pattern. The *SD* of other joint orientation angles (L4/L5, C7) did not reveal any significant changes among the conditions. However, similar trends were observed in which the smallest joint orientation angle variation occurred while utilizing an external focus. The relatively small amount of movement over those joints may result in the incapability of detecting the effect of attentional focus. Indeed, the decreased movement of the distal part of joints may be a strategy of how the human body maintains the balance in an upright posture.

The pattern of results were opposite of what we expected and not consistent with the previous dart-throwing study which showed larger joint movement variation of the shoulder and elbow with an external focus (Lohse et al., 2010). Compared to this study, different tasks may require a unique strategy for controlling the movement in order to achieve the goal. For dart throwing, in order to complete the task, those joints required reasonable movement to throw the dart. In this study, minimizing the joint movement especially in the lower extremity may be essential to maintain the COP within the base of support while balancing on the discs. Therefore, less joint movement may lead to a better balance performance indicated by smaller *SD* of COP trajectory. One previous motor learning study discovered that as participants improved their balance performance toward the end of practice on a stabilometer, they saw smaller *SD* of joint angles (Caillou et al., 2002). Another balance learning study also revealed that higher frequency and lower amplitude of movement adjustments were associated with the external focus relative to the internal focus condition (Wulf, McNevin, & Shea, 2001). Those results could explain why better balance performance while adapting an external focus would associate with smaller *SD* of joint movements.

The Effect of Attentional Focus and Task Difficulty on the Variance in the Joint Space

The individual joint variance from the traditional method may not provide a holistic picture of how attentional focus affects the overall joint coordination. The main purpose of this study was to utilize a UCM approach to investigate the effect of attentional focus on the structure of movement variability with respect to controlling the COM while balancing with various levels of difficulty. It was expected that the V_{UCM} would be larger and V_{ORT} would be smaller in an external focus compared to an internal focus in a difficult balancing task, whereas no differences between two focus conditions in an easy balancing task were expected.

Unexpectedly, the V_{UCM} which is the variability that does not destabilize the performance was decreased in an external focus condition with reference to baseline across both difficulties. On the other hand, the V_{ORT} represented as the variability destabilizing the performance variables showed no differences among three conditions. One possibility is that the strategy of this balancing task is different than others. The attentional focus cue seems to restrain a certain degree of freedom in order to stabilize the location of COM within the base of support. This finding was also consistent with the results from the traditional *SD* of orientation angles which indicated the lesser movement of joints in the sagittal plane while adopting an external focus.

It is also interesting that the interaction between difficulty and focus condition for V_{UCM} was close to being significant. The pattern behaved differently from the difficult to easy version of the task among the three focus conditions. In the baseline, V_{UCM} was higher in the easier version of the task, but in the internal focus condition, V_{UCM} was higher in the more difficult version. However, in the external focus condition, V_{UCM} of both difficulties were almost identical. It seems to be an internal focus may have freed certain degrees of freedom in the more difficult version of the balance task. This result also corresponded to the increase of movements around the knee, hip, and L4/L5 joints in the difficult task while using an internal focus. Under larger disturbance, it may allow a larger solution space with respect to such performance variables, therefore, increased V_{UCM} would be expected. On the other hand, for the external focus, the movements were relatively stable in both difficulties of the task which resulted in a similar V_{UCM}.

A previous study investigated the effect of attentional focus on the structure of variability while hopping in place (Fietzer et al., 2018). They found that both external and internal focus had larger V_{ORT} with respect to the leg orientation stabilization at takeoff and landing compared to the natural condition, however, there were no differences between the two focus conditions. In terms of V_{UCM} related to controlling the leg orientation, there were no differences among the conditions. Although the results were contrary to the authors' hypothesis that directing attention externally would increase V_{UCM} and decrease V_{ORT} resulting in greater leg orientation stabilization, the authors suggested that the decrease in stabilization of leg orientation was contributing to the flexibility within the system for hop location accuracy. In this case, the orientation at takeoff and landing did not affect the hopping accuracy which indicated that the strategy of hopping in place was not "controlling" the orientation of leg. Compared to the current balance task study, balance performance measured by the *SD* of COP trajectory was directly reflected by controlling the COM, therefore, destabilizing the COM would be to the detriment of the balance. Although it did not exhibit the flexible utilization of joint configuration under the external focus condition, decreasing variability that disturbed the COM stabilization occurred while adopting an external focus. Taken together with the improvement in balance performance, lower V_{UCM} is not detrimental in this task.

These results were inconsistent with previous researchers' assertions that an external focus could promote greater functional variability (Lohse et al., 2010; Wulf & Dufek, 2009). Although we found the benefit of an external focus in terms of decreased magnitude of error in this study, the mechanism of how an external focus regulates the movement pattern to achieve a superior balance performance continues questionable. Numerous researchers have suggested that increasing variability would allow the movement to be adopted in a functional way and not fixed into a rigid solution when adjustment for changes in a dynamic environment is required (Davids et al., 2003; Stergiou et al., 2006). A previous study has observed higher V_{UCM} in healthy young adults arranged their joint motion of the foot, ankle, knee, hip-trunk, cervical, and upper cervical joints responding to support surface perturbations by returning the COM to the pre-perturbation state (Scholz et al., 2007). It suggested that healthy young adults utilize more flexible patterns of joint coordination to stabilize the COM, which allows the body to adapt to the effects of unpredictable perturbations from the environment. In the present study, it was anticipated that an external focus would present a similar benefit, but it did not. Future research may consider replicating the present design in a task similar to that used by Scholz et al. (2007) that involves a reactive balance demand as opposed to the steady-state balance demand in the present study.

Under the commentary in favor of higher functional variability, this balancing task conducted in the lab setting may not create enough active changing scenarios as activities of daily living, therefore, increasing the variability may not be essential. The speculation could be that an external focus could encourage the more efficient movement which may not be necessary to increase the variability. UCM analysis is a relatively contemporary assessment for the nature of variability by extracting them into two categories: performance-irrelevant and performance-destabilizing (Scholz & Schöner, 1999). Applying this approach to various type of tasks could give us a more detailed understanding of how movement variability is changed due to attentional focus as well as the underlying mechanism of the advantage of external focus in tasks with varying demands.

Limitations and Future Considerations

The study assumed that participants would be compliant with the different verbal instructions trial by trial. Percentages of ability to follow instructions and rate of compliance with respect of task duration across condition in the self-report manipulation check in this study are presented in Table 8. Unfortunately, it was not possible to objectively measure the exact compliance of each participant during each trial. However, over 94% of participants reported they could follow the instructions for each attentional condition based on the self-report manipulation check in this study. For the rating of the compliance with the instructions, participants rated that they focused on the internal focus condition 64.8% of the time, and the external focus condition 70.4% of the time. Compared to the previous pilot study, the compliance rate in this study is considerably higher. The task in the pilot study was 20-s duration per trial. A recent study conducted by Microsoft in Canada (Consumer Insights, 2015) reported that the average attention span dropped from 12 s in the year 2000 to 8 s in the year 2013 It appears that the 10-s protocol in the current study may have led to greater compliance with focus instructions.

Table 8

Manipulation check

Condition	Questions	Percentage
Internal Focus	Were you able to focus on keeping ***your feet*** still when told to do so?	94.4
	What percent of the time were you successful in using this instruction?	64.8
External Focus	Were you able to focus on keeping ***the discs*** still when told to do so?	94.4
	What percent of the time were you successful in using this instruction?	70.4

Another limitation of this study was the short-term protocol. Attentional focus consistently affects both performance and learning (Wulf, 2013). The primary goal of this project was to investigate if the attentional focus could provoke an instant impact on the structure and magnitude of movement variability, but it would also be useful to understand if this effect persists in longer training duration. Future work should consider employing a learning or training protocol to determine if attentional focus continues to influence the structure of movement variability over time.

With regard to the task difficulty in this study, it should be noted that there was a main effect of difficulty. Unexpectedly, the results revealed that participants perform better on balancing in a squatting position than standing upright on inflatable balancing discs. One possibility is that holding a squatting position would move the COM downward and provide an advantage of controlling COM trajectory within the base of support. Although squatting required higher muscular demand than standing, the benefit of lower COM may mitigate the difficulty. Future studies should consider manipulating only one factor affecting the balance at one time to determine the task difficulty. Also, due to the subjective nature of task difficulty, it is challenging to identify at what point attentional focus would or would not impact balance performance. A repeated measures design with several levels of task difficulty may be useful in providing further clarity to this issue.

Regarding the practical application of attentional focus on the balance task using inflated discs, it could be beneficial for older adults and those with fall risk especially in patients in the hospital or nursing home. Considering younger and older adults experience a similar benefit of an external focus of attention (Chiviacowsky et al., 2010; Rhea et al., 2018), the positive result in this current study may generalize to the older adult population. Several studies (McNevin et al., 2003; Wulf et al., 1998; Wulf, McNevin, & Shea, 2001) including the current result have demonstrated that using an external focus reduces the magnitude of movement error relative to an internal focus, and the recent study also suggest an advantage in the structure of movement variability (Becker & Hung, 2020). However, this study observed the lesser functional variability while adopting an external focus. It would be interesting to examine how the functional variability influences the risk of fall. Comparison of people with high falling risk with healthy age matched controls in terms of functional variability during the balance task is warranted.

Conclusion

This study demonstrated that shifting attentional focus alters the structure of movement variability as well as the magnitude of variability in ankle, knee, and hip orientation angles during the balancing task. An external focus decreased movement of the ankle, knee, and hip as well as the flexibility of joint utilization to maintain the COP reflected by a lower goal-equivalent (V_{UCM}) variability. An external focus, but not internal focus, increased the stabilization of COP in the antero-posterior direction relative to the baseline. The lower magnitude of movement variability with an external focus was contrary to previous work (Lohse et al., 2010; Wulf & Dufek, 2009), though it is acknowledged that the demands of each task studied may reflect different needs for movement variability. While behavioral benefits of an external focus are consistent, the assertion that an external focus promotes greater functional movement variability requires further study with an array of motor tasks to determine the veracity of the claim.

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