Movement Variability As a Clinical Measure for Locomotion

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The purpose of this paper is to discuss the role of variability in human movement, with emphasis on locomotion variability. Based on the assessment of stride characteristics, movement variability has been associated with reduced gait stability and unsteadiness. However, based on the measure of joint coordination during locomotion, variability has been suggested to provide a source of adaptation. Therefore, it would appear that the assessment of movement coordination from either the task outcome (i.e., stride characteristics) or the joint coordination patterns provide distinctly opposing views of variability. This paper will discuss the use of the variability measures, specifically joint coordination variability, from a clinical perspective. Investigations will be presented in which a reduction in joint coordination variability has been associated with pathology. Finally, the clinical implications of these measures as well as treatment suggestions are discussed.

Key Words: joint coordination, stride characteristics, movement dysfunction

Introduction

Coordination variability is an area of increasing study among movement scientists. In addition to its use with skill acquisition (Beek, 1989; Hausdorff et al., 1999), trial-to-trial variability within subjects has recently been employed as a clinical measure. Specifically, movement variability in many gait parameters has been demonstrated to be a discriminating factor between non-impaired individuals and those with various clinical pathologies. However, depending on the gait parameter, variability has been suggested to serve opposing roles. While variability in stride characteristics are traditionally viewed as a limitation to successful locomotion (Gabell & Nayak, 1984; Hausdorff et al., 1998), evidence has indicated variability in joint coordination to be an essential component, providing the necessary flexibility for successful task execution (Clark & Phillips, 1993; Turvey, 1990; van Emmerik et al., 1999).

Variability and Stride Characteristics

In regard to human walking, an increase in the within-subject variability of stride characteristics has been regarded as an indicator of unsteady gait, and has been characterized as

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Gabell and Nayak (1984) measured the step-to-step variability of double support and stride time, and demonstrated increased variability to predict an individual’s risk of falling. Hausdorff et al. (1997) assessed the variability of stride duration, as well as stance and swing duration, to be greater among elderly fallers compared to elderly non-fallers or young subjects (Figure 1). In addition to temporal measures displaying increased variability, stride-to-stride variability of spatial gait parameters, such as stride length, has also been associated with falling (Maki, 1997; Nakamura et al., 1996).

The speed of locomotion has been demonstrated to influence the level of variability. Near the walk-run and run-walk transition regions of gait (i.e., 2.0–2.2 m · s⁻¹), stride duration variability increases (Brisswalter & Mottet, 1996), with a consistent level of variability observed before and after the transition. Stride duration variability has also been revealed to increase at slow walking speeds (0.2–0.6 m · s⁻¹) compared to speeds ranging from 0.8–1.4 m · s⁻¹ (van Emmerik et al., 1999). Figure 2 displays the variability of stride duration (van Emmerik et al., 1999), indicated by the coefficient of variation (ratio of standard deviation and mean), as walking speed was systematically increased and decreased.

In addition to being associated with falling, increased stride characteristic variability has also been demonstrated among individuals with neuromuscular diseases. Measuring the stride-to-stride variability in stride time and double support time, Hausdorff et al.

![Graph](image)

**Figure 1** — Stride-to-stride variability of temporal stride characteristics while walking for 6 min at self-selected pace. Coefficient of variation was defined as the ratio of the standard deviation to the mean value. The young subjects (25 ± 2 years) and elderly nonfallers (77 ± 4 years) displayed similar temporal variability, while the elderly fallers (82 ± 5 years) displayed dramatically greater variability than either group. (Adapted from Hausdorff et al., 1997.)
(1998) investigated movement coordination among persons with Huntington’s disease and Parkinson’s disease. In comparison to age matched non-impaired individuals, both patient groups displayed greater variability, suggesting variability to be associated with neurological diseases. Similar increases in stride characteristics (both spatial and temporal) have been demonstrated in adults with cerebellar ataxia, subcortical arteriosclerotic encephalopathy and congestive heart failure (Hausdorff et al., 1994; Palliyath et al., 1998; Ebersbach et al., 1999), as well as children with spastic cerebral palsy (Steinwender et al., 2000). It should be noted, however, that the above investigations of stride characteristic variability among individuals with various pathologies did not control for the speed of locomotion, as the patients were allowed to walk at self-selected speeds. In general, the patients selected slower walking speeds than the non-impaired subjects (Ebersbach et al., 1999; Palliyath et al., 1998; Steinwender et al., 2000). As demonstrated by both Brisswalter and Mottet (1996) and van Emmerik et al. (1999), walking speed can affect the observed variability of stride duration. Therefore, the observed increase in stride characteristic variability may be attributed to the difference in walking speed and not necessarily the pathology.

Variability and Joint Coordination

The association of increased variability in stride characteristics with reduced gait stability and unsteadiness (Hausdorff et al., 1994; Maki, 1997; Nakamura et al., 1996) suggests
that movement variability is undesired. However, variability should be considered relative to the movement measure (Newell et al., 1993); therefore, its role may not be generalized. Specifically, variability in joint coordination during gait has been suggested to provide a level of flexibility and adaptability (Clark & Phillips, 1990; Holt et al., 1995). Holt and colleagues (1995) demonstrated the coordination patterns of the ankle-knee, ankle-hip, and knee-hip couplings possessed a certain degree of variability during walking. They concluded the variability present in the lower extremity joint coordination was an essential part of the task (walking), providing the flexibility to adapt to perturbations and attenuate impact shocks. This supports Kelso’s (1995) hypothesis that pattern fluctuations (variability) provide flexibility and are a source of positive noise.

Bernstein (1967) defines movement coordination as the mastering of redundant degrees of freedom to produce a controllable system. The formation of coordinative structures between the multitude of joints, muscles, and nervous innervation present in the extremities and trunk allows a reduction in the functional degrees of freedom to a more controllable level. A coordinative structure can be described as a functional synergy between neurons, muscles, and joints. While capable of performing independently, each component of the synergy can become functionally linked to behave as a task-specific unit (Turvey, 1990). In view of such a large number of degrees of freedom, variability in the formation of these coordinative structures would seem inevitable. The same task may be accomplished using different degrees of freedom while, conversely, the same degrees of freedom coordinated differently may accomplish different tasks (Bernstein, 1967). This variability in coordination has been suggested to provide a level of flexibility in task execution (Turvey, 1990). Thus, variability may be an important component of coordination. By limiting an investigation to the outcome of a task (i.e., stride characteristics), the variability in the motor patterns used to accomplish the outcome is ignored. It would appear, therefore, that measuring the outcome of the task alone provides an incomplete analysis of human movement coordination.

Arutyunyan et al. (1969) demonstrated a redundancy of movement solutions in accomplishing a particular task. While displaying low variability in achieving the task criterion, expert marksman displayed a variety of joint coordination patterns. Thus, a consistent outcome in the end-effector was achieved via a variety of coordinative structures. Morasso (1981) observed similar movement variability during point-to-point reaching tasks. The hand trajectories displayed common features across a variety of reaching locations, while the joint trajectories varied substantially. Therefore, it would appear that assessment of movement coordination from either the task outcome or the joint coordination patterns provide distinctly opposing views of variability.

Investigations of joint coordination during gait have further demonstrated an apparent intrinsic variability. Based on relative motion diagrams and a vector coding technique described by Sparrow et al. (1987), Heiderscheit (2000) assessed the lower extremity joint coordination during running at preferred speed and fixed speed (2.68 m · s⁻¹). Distinct regions of variability were observed in intralimb and interlimb couplings during changes in coordination states among non-impaired individuals. These regions corresponded to reversals in the direction of motion of one or both components in the coupling. For example, Figure 3 displays the coordination and corresponding variability for the intralimb coupling of knee flexion/extension and ankle inversion/eversion. When either the knee or ankle reversed the direction of motion, an increase in coordination variability is observed. The reversal of direction of motion in joints has been hypothesized to be a critical event in investigating movement coordination. Clark and Phillips (1993) suggest that reversing the direction of motion of the joint or segment is a major control issue for the neuromuscular system. Ghez and Sainburg (1995) observed joint coordination variability
Figure 3 — a) Relative motion plot of knee flexion (+) / extension (–) and ankle inversion (+) / eversion (–) during running at 2.68 m·s⁻¹. Using a vector coding technique described by Sparrow et al. (1987); b) joint coordination of 15 strides; and c) assessment of corresponding variability. The stride is defined with heel-strike of the same limb at 0 and 100% and toe-off at 45%. Increases in variability correspond to changes in the coupling angle of the joints.
at direction reversal to be greater than the variability observed when the joints maintained a constant direction of motion. Further, individuals with reduced proprioception have the most difficulty performing direction reversals during a movement task, as indicated by increased variability (Ghez & Sainburg, 1995; Sainburg et al., 1995). Therefore, greater variability observed at direction reversals may be anticipated based on the neuromuscular complexity of the task.

Variability has also been demonstrated in the coordination of the pelvis and thorax during walking (van Emmerik & Wagenaar, 1996). Using continuous relative phase, trunk coordination was assessed among non-impaired subjects, while walking speed was systematically increased and decreased. Coordination variability was observed to increase at speeds associated with a shift in the pelvic-thoracic coupling coordination (0.6–1.1 m · s⁻¹). That is, increased pattern variability was present during the transition from in-phase to anti-phase, as well as the reverse. The increased variability was considered necessary for the coordination pattern change, as it was indicative of a loss of pattern stability.

**Joint Coordination Variability and Pathology**

While joint coordination variability has been identified among non-impaired individuals, its reduction has been associated with pathology. The coordination of the pelvic-thoracic coupling during locomotion was compared between individuals with Parkinson’s disease and age-matched non-impaired individuals (van Emmerik et al., 1999). Once again, the coordination was assessed at various speeds of locomotion (0.2–1.4 m · s⁻¹). The continuous relative phase between the pelvic and thoracic segments revealed that the individuals with Parkinson’s disease displayed greater axial rigidity as indicated by decreased changes in relative phase values across all speeds. The authors concluded that the observed decrease in relative phase variability contributed to the inability of the individuals with Parkinson’s disease to change the axial coordination pattern from in-phase to near anti-phase at faster locomotion speeds. Despite the significant between-group differences in axial coordination, no difference between groups was observed for stride duration and its variability (Figure 2). This lead the authors to conclude that the traditional stride parameters were not sensitive enough to detect movement coordination differences when locomotion speed was controlled (van Emmerik et al., 1999).

Hamill et al. (1999) described preliminary results of reduced variability in subjects with orthopaedic injury. The variability in the coordination of lower extremity intralimb couplings was compared between subjects with and without patellofemoral pain during running at a fixed speed (2.68 m · s⁻¹). Using relative phase as the coordination measure, reductions in joint coordination variability were present in many of the couplings among the patellofemoral pain group. Reduced variability without any neurological disease led the authors (Hamill et al., 1999) to suggest that the knee pain experienced by the individuals with patellofemoral pain diminished the joint coordination variability by constraining the available movement patterns. Of all possible movement patterns, a select few may be performed with minimal or no pain. Therefore, the individual with patellofemoral pain may consistently utilize these few patterns to minimize pain.

Heiderscheit (2000) also investigated movement variability among individuals with patellofemoral pain. Based on relative motion diagrams, a reduced variability at heel-strike for the transverse plane rotations of the thigh and leg was observed among the injured leg of the individuals with patellofemoral pain in comparison to non-impaired controls. In addition, the stride length variability was observed to increase in the same subjects. To assess the role of pain in the observed changes in movement variability, the gait analysis was repeated following treatment of the patellofemoral pain. With an average
pains reduction of 60%, the stride length variability decreased, accompanied by an increase in the variability of the thigh:leg rotation coupling. The response of movement variability to a change in pain (Heiderscheit, 2000) provides support to the hypothesis of Hamill et al. (1999).

Reduced variability of the between-joint coordination was also identified in the affected limb of children with spastic hemiplegic cerebral palsy (Jeng et al., 1996). The reduced variability was suggested to have occurred due to neural and mechanical deficits producing tightly constrained, stereotypical coordination. In addition, the non-affected limb revealed an increase in variability compared to non-impaired children. The authors concluded that the increased variability of the non-affected limb provided a means of adaptation.

Besides locomotion, a functional role of physiological variability has been demonstrated in a variety of biological systems. Investigations into healthy cardiac function have revealed a level of variability and irregularity in heart rate that was previously thought not to exist. In addition, cardiac pathologies display a stable, consistent heart rate. For example, following an acute myocardial infarction, a decrease in heart rate variability was a strong predictor of mortality (Kleiger et al., 1987). Hon and Lee (1965) revealed a decrease in heart rate variability to be correlated to a lower fetal survival rate. Variability has also been demonstrated in mammalian cutaneous mechanoreceptors (Collins et al., 1996), muscle-spindle receptors (Cordo et al., 1996), and electroencephalogram (EEG) signals during sleep (Berry et al., 1998). Newell et al. (1993) observed a reduced movement trajectory of the center of foot pressure among patients with tardive dyskinesia as compared to non-impaired individuals. Tardive dyskinesia is a movement disorder marked by involuntary stereotypical movements that can occur secondary to prolonged use of neuroleptic medication. The reduced variability was believed to contribute to observable postural problems.

**Clinical Implications**

As is evident from the preceding examples, variability in joint coordination appears to have a necessary role in human movement. The variability is a part of the dynamics of the movement and as such can be altered by changes in the movement itself. Increasing the speed of locomotion can result in distinct changes in the coordination pattern and corresponding variability (van Emmerik & Wagenaar, 1996). In addition to speed manipulation, Wagenaar and van Emmerik (1994) incorporated an external auditory rhythm for individuals with Parkinson’s disease to move their arms and legs, and observed a reduction in the characteristic axial rigidity. The use of an orthotic device has also been regarded as an environmental change that can impact the overall system dynamics (Kamm et al., 1990). Without containing instructions for a different pattern of movement, the orthotic can disrupt the current pattern, providing an avenue to seek a potentially better one.

The presence of variability can indicate an impending change in the movement pattern. Referring to the dynamical systems theory, this information can be valuable to the clinician in treatment of movement disorders. In general, the observed dynamics of identified variables are utilized to understand the process of pattern change. Once the process is determined in non-impaired individuals, it can be applied to those with movement dysfunction. Scholz (1990) provides a review of the dynamical systems theory and how it can be incorporated into therapeutic practice.

From a clinical perspective, treatment of movement dysfunction may be most effective when the system is in transition (i.e. increased pattern variability). If a consistent, stable pattern is observed, attempts to improve the movement dysfunction may prove ineffective (Kamm et al., 1990). The presence of variability indicates the system to be in a
more flexible state, allowing therapeutic interventions to be more effective. Kamm et al. (1990) discuss providing a safe yet progressively unstable environment for the patient, thereby allowing the patient to explore the movement boundaries. For example, altering the locomotion speed or surface to be more challenging may elicit a change in the movement coordination displayed by the patient. This change in the movement pattern is typically preceded by an increase in its variability.

Conclusions

This paper has addressed the role of movement variability relative to the particular movement parameter. In addition, locomotion variability among both non-impaired and pathological populations was discussed. The variability differences observed between these groups suggest the use of movement variability as a discriminating measure and possible clinical tool. Based on this information, rehabilitation clinicians can incorporate measures of movement variability to aid in the design of appropriate treatment programs directed at these deficits.

References


