USING COORDINATION MEASURES FOR MOVEMENT ANALYSIS

Joseph Hamill[1], Jeffrey M. Haddad[2], Richard E. A. Van Emmerik[2]
[1]Biomechanics and [2]Motor Control Laboratories, University of Massachusetts, USA

Traditionally, in biomechanics we have investigated the actions of single joints or segments without taking into account the interactions of these structures. A dynamical systems approach has been increasingly used in biomechanics to give a different perspective on the interaction of specific structures in human movement. That is, the study of coordination has become more prominent in the biomechanics literature based on the work of Bernstein (1967). Coordination is defined as overcoming excessive degrees of freedom thereby turning individual movement elements into a controllable system. In this paper, we will describe a theoretical framework for analyzing coordination, present examples in the literature and discuss future developments for this type of analysis.

KEY WORDS: dynamical systems, phase angle, discrete relative phase, continuous relative phase

INTRODUCTION: The majority of the studies in the biomechanics literature have reported the kinematics or kinetics of individual joints or segments rather than addressing the interaction between these joints or segments. While valuable in itself as a description of the movement of a segment, we must note that the human body is made up of multiple joints and segments that must operate in a smooth, harmonious pattern to produce movement. Thus, we must have a theoretical framework from which we can describe the interactions, that is the coordination, of the different joints or segments. The work of Bernstein (1967) has provided a framework with which we can study movement coordination and movement control. According to Bernstein, coordination is not defined as the action of single elements but is the common action of separate elements. Specifically, he described coordination as overcoming excessive degrees of freedom.

In biomechanical systems, there are generally a high number of degrees of freedom defining the system. We can reduce the available degrees of freedom by forming coordinative structures, a concept derived from Bernstein's work. Coordinative structures can be defined as muscle synergies that span several joints and are functionally linked to satisfy task demands (Turvey, 1990). They also allow the system to achieve the same goals by using different degrees of freedom and/or use the same degrees of freedom to achieve different movement goals.

Kelso (1995) developed a dynamical systems approach to study movement coordination and the stability features of coordinative structures. These tools have been used to identify the transition processes and stability in human movement. From this perspective, the essential element in transition processes is the degree of variability in the coordinative structures. Variability can be instrumental in inducing a coordination change or to establish a combination of stability and flexibility of movement.

The purpose of this paper is, therefore, to describe how coordination measures may be used in the analysis of human movement. We will discuss computational methods, the interpretation of coordination measures and provide examples from the literature in which these measures have been utilized.

ASSESSING COORDINATION: Several researchers (e.g. Haken et al., 1985) considered phase relationships or the relative phase between different oscillators or elements (i.e. joints or body segments) as a measure of coordination. The relative phase between oscillators can help to identify different qualitative states of the system dynamics that can be used to identify changes in coordination. Changes in movement patterns can be evaluated using either discrete or continuous measures of relative phase.

To determine the discrete relative phase (DRP) measure, the difference in timing of two elements is calculated. This difference may be calculated, for example, when two joints or two segments reach their maximum value. DRP can be calculated using the formula:

$$\phi = \frac{t_1 - t_2}{T} * 360^{\circ}$$

Where Φ is the phase angle, t_1 and t_2 represent time to the critical point of interest of each element and T is the cycle time.

In continuous relative phase (CRP), the relative phase between two elements (i.e. joints or segments) is measured throughout the movement cycle. To begin, we determine the phase plane of each element. One method to construct the phase plane, for example, is accomplished, after sufficient normalization procedures, by plotting the position of the element signal versus the velocity of that element (see Figure 1a). The phase angle in the phase plane is then determined at each instant in time (Figure 1b). To calculate CRP between the elements, the phase angle of one element is then subtracted from the phase angle of a second element. For example, if we wished to determine the CRP between thigh and leg flexion/extension we would use the following formula:

$$\text{CRP } (t) = \Phi \text{ Thigh } (t) - \Phi \text{ Leg } (t)$$

Where Φ Thigh (t) is the phase angle of the thigh at time t and f Leg (t) is the phase angle of the leg at time t. It should be noted that it cannot be determined from the CRP profile which element is leading and which is lagging only that the two elements are either in or out of phase.

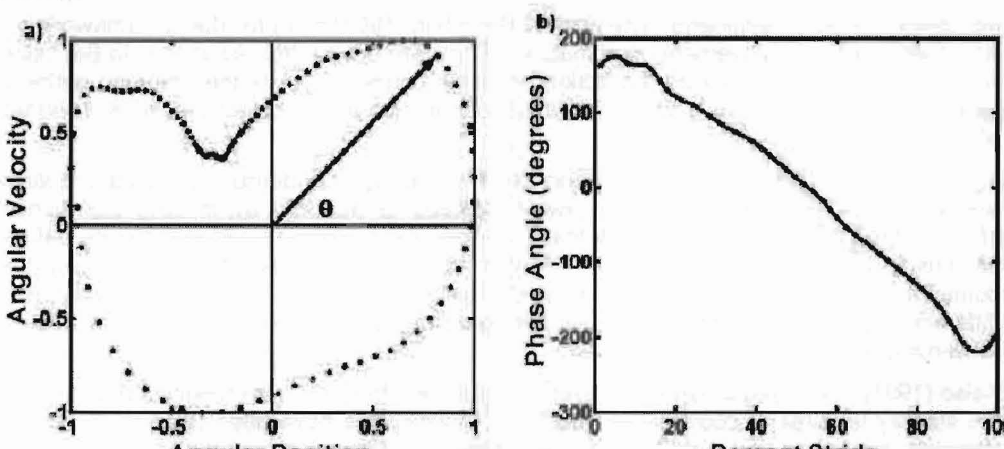

Figure 1: a) normalized position – velocity phase plane of the left thigh segment across the entire stride. b) phase angle at each data point is calculated using a four quadrant arctangent function.

To determine the variability of CRP, we use multiple cycles of the specific movement (Figure 2a). Each CRP profile is interpolated so that each will have the same number of data points. The cycles are then averaged on a point-by-point basis and the standard deviation of each point of the ensemble curve is calculated (Figure 2b).

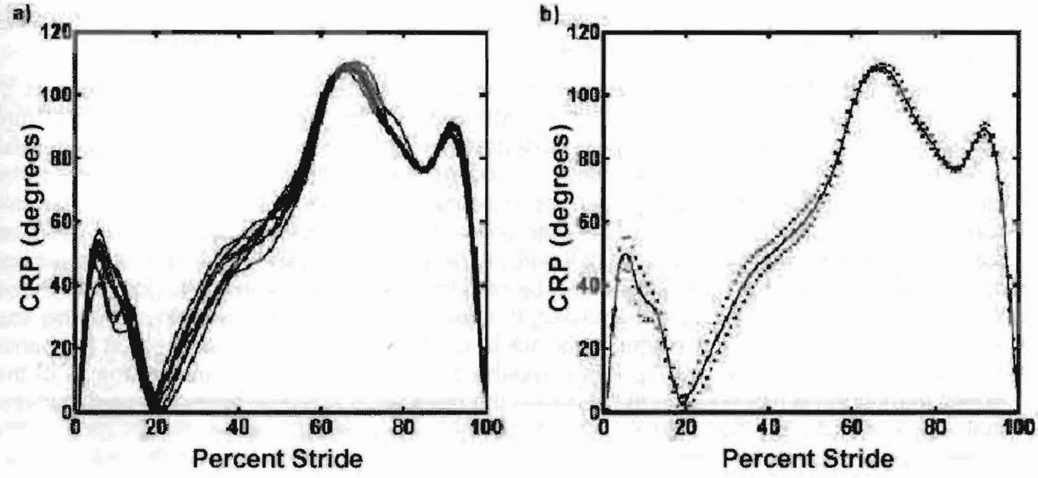

Figure 2: a) Continuous relative phase in the thigh-leg coupling over 10 strides of walking on a treadmill. b) Mean CRP (solid line) in the thigh – leg coupling +/- one standard deviation (dotted lines). The bandwidth between the standard deviation curves provides information on the stride by stride coupling variability at each point in the stride.

When calculating continuous relative phase, issues such as phase plane construction and normalization must be carefully considered (see Hamill et al., 2000 for a review). Also limitations in the interpretation of these measures must be realized (see Fuchs et al., 1994 and Peters et al., 2003 for a review). Finally, many other measures (including cross correlation measures, vector coding techniques, and Hilbert transforms) have been successfully applied to a wide range of human movements to assess coordination. No one measure is better than the others; rather the best measure to use depends on the nature of the data and the research question of interest (see Van Emmerik et al., 2004 for a comprehensive review of different coordination techniques).

COORDINATION IN SPORTS: Coordinating and controlling the body's segments during most sport activities is not a trivial task. During the sporting event, the body typically performs a variety of movements requiring different amounts of force and precision. As these movements are being performed, internally generated forces and external reactive forces act upon the body's degrees of freedom. This adds a large amount of context-conditioned variability to the generated movements (Turvey 1990). In other words, the same descending motor command may cause two completely different movements based upon the forces acting on the body. For example, a command from the motor cortex that causes the arm to flex in one situation may cause the arm to simply stop moving in a situation where the arm was going through an extension movement.

Although control of the body's many degrees of freedom can sometimes be difficult (in both sports and every day life), the redundancy inherent in these degrees of freedom allow for smooth coordinated movements to be produced. In sports, the amount of coordination (and also expertise) in an event is usually determined by the skill level of the athlete. When first learning a sport, novices will tend to become very rigid and freeze out degrees of freedom As their skill level increases, degrees of freedom are released and movements become more fluid and coordinated (Vereijken et al., 1992). Releasing the degrees of freedom allows the athlete to produce more efficient movements that exploit the forces acting on the body. During the course of motor learning, the individual may attempt to perform a given movement using a variety of different body movements and configurations. Because of the redundancy in the degrees of freedom the individual can produce the same motor solution from a variety of different motor patterns. This variability in movement may allow the individual to explore the dynamical layout of the task and ultimately discover the best strategies for the successful completion of the task (van Emmerik et al., 1989).

Research suggests that the body forms coordinative structures to control the many degrees of freedom. As previously mentioned, a coordinative structure is essentially a temporary functional linkage of two or more individual degrees of freedom that are used in the successful completion of the task. For example, skilled marksmen show little variability at the barrel of the gun. However, these individuals have more movement at the individual segments of the arm compared to unskilled shooters. The marksmen appear to form a coordinative structure comprising of the muscles and joints of the upper arm, lower arm and wrist. Here a movement or perturbation one joint is instantly offset by counter movements at the other joints so that a stable endpoint is maintained. In unskilled shooters, the degrees of freedom about the arm are not coordinated with each other. This lack of coordination causes movement at the barrel endpoint (Arutyunan et al., 1969). The variability observed in the joints and segments of the skilled marksmen is functional in that it allows the marksman to better overcome perturbations that may occur during the course of the movement. For example, some perturbation at the upper arm can be quickly offset by the lower arm thus allowing the endpoint to remain stable. The rigid arm posture adopted by the novice is not functional in that any perturbation of the arm is quickly transmitted to the barrel of the gun. This concept is applicable to most sports where coordinative structures that allow some movement at the individual segments are beneficial in producing skillful movements.

In a recent study, Moir (2004) used coordination measures to explore the effect of resistance training on performance during accelerative sprinting. It was hypothesized that increases in strength could affect accelerative sprinting. Moir suggested that changes in coordination could follow large changes in strength. However, with small increases in strength, any changes in the coordination pattern would be minimal. The results indicated that the sprinters maintained their well-learned coordinative pattern rather than adapt a new pattern in the absence of large strength gains.

It appears that successfully completing a sporting event requires multiple body segments and joints to be coordinated. However, the traditional biomechanical variables that have typically been used to examine the actions and movements of various sports techniques are limited. That is, they do not provide information as to how multiple joints or segments are coordinated or work together. For example, movements about the knee may be more meaningful when measured together with movements about the ankle joint than when studied in isolation from other movements. The techniques outlined above in the previous section extend beyond traditional biomechanical variables and provide a mechanism over which high skill movements in a multi-articular body can be quantified. These techniques may provide a valuable mechanism for quantifying coordination in different sports, and can provide information regarding the control of degrees of freedom and formation of coordinative structures between skilled and unskilled individuals.

COORDINATION AND INJURY: A very important aspect of investigating sports activities involves athletic injuries. It is critical for athletes and coaches to know the mechanism for the cause of the injury in order to determine how to prevent the injury. Recently, several researchers have suggested using coordination measures to investigate cumulative trauma or overuse injuries (Hamill et al., 1999) while others have investigated specific injuries using these techniques (e.g. Heiderscheit et al., 2002; Pollard et al., in press).

Hamill et al. (1999) illustrated the use of a CRP analysis of the lower extremity to hypothesize the nature of the occurrence of an overuse injury. Using only a few subjects, the authors suggested that a relatively higher CRP variability was the healthy state and that a relatively lower CRP variability was an indication of injury. They did not, however, identify the window below which an athlete would be prone to injury. In addition, they could not determine whether the lower CRP variability was the cause of the injury or the result of the injury. Heiderscheit et al. (2002) used the concept presented in the previously discussed study to investigate subjects with and without patellofemoral pain (PFP) during running. Utilizing the same couplings and a vector coding technique, these authors presented results consistent with the Hamill et al. (1999) paper. The relative phase variability in the PFP patients during running was lower than in the healthy control subjects.

In a recent study, Pollard et al. (in press) suggested that a randomly cued cutting task would be an effective protocol to study the gender issue in anterior cruciate ligament injuries (ACL). They compared healthy males and females accomplishing the randomly cued cutting task using the same procedures as in the Heiderscheit et al. (2002) paper. The premise of the paper was that females, having a significant propensity of incurring an ACL injury, would exhibit relatively lower CRP variability than the males while accomplishing the cutting task. The authors reported that indeed the females had lower CRP variability than males (Figure 3).

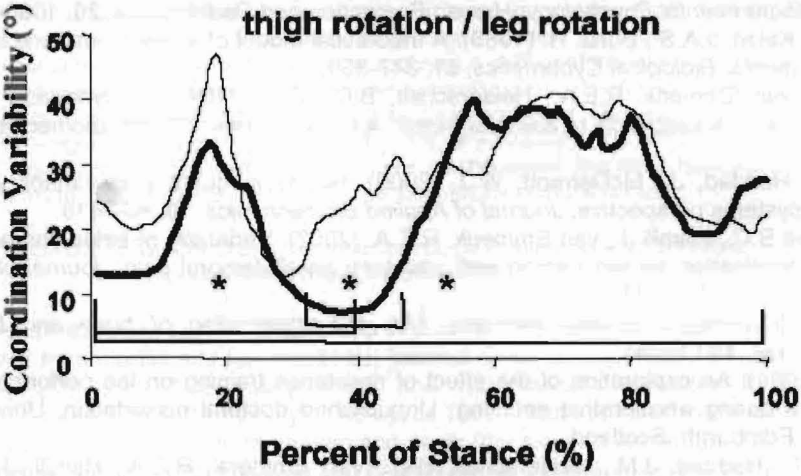

Figure 3: Coordination variability in the thigh rotation-leg rotation coupling the support phase during a randomly cued cutting maneuver for females (thin line) and male (thick line). Asterisks indicate periods that were significantly different.

FUTURE DIRECTIONS: In the sports realm, the techniques discussed above have not been extensively utilized. To date most biomechanical research in athletics has been mostly descriptive in nature, where specific kinematic and kinetic properties of an event are outlined. This type research has been good at describing movements of specific segments during the course of the event and has been used by coaches to make suggestions regarding training or to assess the benefits of different training regimens. One issue with this type of research is that it does not utilize measures that examine the coordination between segments. Most sporting activities by definition involve simultaneous movement of many of the bodies segments. Valuable information with regards to the dynamics of the movement can be lost if each of these segments are examined in isolation. For example, in the clinical realm the higher order analytical techniques described in this paper have provided new insights into the variability that is often observed in the motor system. Variability between successive movements was once though to be pathological. Newer views now suggest some amount of controlled variability in the motor system may provide informative information to the body's perceptual systems regarding the dynamical properties of the body's interaction with the environment (Riccio & Stoffregen, 1988). The development of these techniques in sports may yield new insights into the nature of motor variability during different sporting events. Variability may not be a property of movement that is detrimental to the successful completion of the sport. Rather, the control of motor variability and how it is interpreted by the body's perceptual systems may be a hallmark difference between elite athletes and those who do not reach elite levels. Elite athletes may be capable of interpreting information from high frequency low amplitude fluctuations and then make the necessary motor adjustments in response to this information. Athletes who do not reach elite status (in spite of the amount of practice) may lack the ability to interpret high frequency sensory information inherent in high frequency fluctuations. This ability would allow the elite athlete to respond to the demands of the event over a very small time scale and may be a hallmark property required to reach elite status.

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