

AN ANALYSIS OF KINETIC RESPONSE VARIABILITY

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ABSTRACT

Studies evaluating variability of force as a function of absolute force generated are synthesized. Inconsistencies in reported estimates of this relationship are viewed as a function of experimental constraints imposed. Typically, within-subject force variability increases at a negatively accelerating rate with equal increments in force produced. Current pulse-step and impulse variability models are unable to accommodate this description, although the notion of efficiency is suggested as a useful construct to explain the description outlined.

INTRODUCTION

Understanding the nature of response variability has important practical and theoretical implications for manual control. In many movement tasks this variability has been recognized as the major limiting factor in performance. The relative scale of such variability may be used as a basis to distinguish between skilled and unskilled individuals. Theoretically, variability expressed in either kinetic or kinematic terms has been viewed as a reflection of the limitations in the neuromuscular system. These have been identified with time constraints of feedback in movement control (Crossman & Goodeve, 1983; Keele, 1968), noise in the neuromuscular system with respect to information transmission (Fitts, 1954) and inherent noise in the motor system itself (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). A detailed analysis of kinetic response can consequently contribute insight into potential sources of limitation in the neuromuscular system and current models of movement control.

There have been a number of attempts to describe the relationship between force production and outcome variability through the use of a variety of motor tasks. The progression of research has been sporadic in terms of chronological development, with each era of activity occurring in seeming isolation with respect to previous efforts. In the following section we review a selection of these studies that have provided bases for the proposed variability functions, with a view to reconciling various inconsistencies that have emerged across experimental situations. We begin by considering force production in isometric

tasks, which are generally considered simpler than isotonic tasks in that changes in limb placement and resulting variation in muscle length do not occur. Force production in isotonic tasks are subsequently examined to provide a foundation for an overall force variability function.

ISOMETRIC TASKS

Perhaps the earliest and certainly one of the most comprehensive studies of response variability is the treatise of Fullerton and Cattell (1892). Superficially, it appears to focus on the problems of perception in a traditional psychophysical analysis of the spatial, temporal and force characteristics related to movement control. However, examination of their experiments indicates that a primary method of measurement was through the use of average error. This procedure required participants to produce a number of responses that were directed at the replication of a criterion target and in essence represents the same procedure currently used to assess force variability. Fullerton and Cattell's results on force production indicated that variable error increased across the force production continuum but that this increase was not linear as would be predicted by a Weberian approach. They suggested that a square-root function was more appropriate in describing the function observed.

Although the work of Fullerton and Cattell represented an early step forward, analysis of the relation between force and force variability was not taken up again until the practical demands of the person-machine interface surface following the Second World War (cf., Fitts, 1947; Hick & Bates, 1950). The study of factors influencing the efficiency of machine controls helped promote an interest in force production. The primary focus of this research was to understand the relation of control dynamics to the accuracy with which movements could be generated particularly in the control of aircraft. In one study, Jenkins (1947) examined the accuracy of force production for stick, wheel and rudder controls. The forces generated ranged from 1 to 60lb and was in part dependent on the task in that less force was needed to move the stick compared to the other controls. The coefficient of variation for the three tasks, that is the standard deviation of force divided by the mean force decreased across the force range selected in the form of a descending exponential. The data for the standard deviation of response followed the general shape as observed earlier by Fullerton and Cattell, that being a progressive increase in variability but with the rate of gain in variability slowing with sequential increments in force produced.

The force variability function obtained by Jenkins appears to be of an exponential morphology, with the change in variability being greatest at low force values. This is demonstrated in both the coefficient of variation and standard deviation functions. The nonproportional relation between force level and force variability was subsequently found by Noble and Bahrick (1956) and Provins (1957), using comparable isometric force generation tasks. Collectively, the data of the immediate post-war period indicate that force variability increases at a decreasing rate with equal increments of force and affirms the general function originally observed by Fullerton and Cattell (1892).

Recently, Schmidt and his colleagues have regenerated interest in the description of force variability and in support of their motor-output variability model presented data indicating a linear relation between variability and absolute level of various movement parameters. In their experiments, subjects were asked to exert isometric forces to shoot a dot on an oscilloscope screen to a height proportional to the criterion peak force. The results exhibited a strong linear relation between the within-subject

variability in force and the amount of force produced. These data are inconsistent with a curvilinear relation that earlier studies might have led us to anticipate, given that the force range used by Schmidt and his co-workers covers the strong curvilinear component of the variability function as reported by Jenkins (1947).

As our synthesis has indicated, the majority of data sets are inconsistent with the finding of a linear and proportional relation between force and force variability. Sherwood and Schmidt (1980) subsequently modified the linear prediction derived from the motor-output variability model not on the basis of previous work, but in response to results from their additional experiment in which variability increased up to approximately 65% of maximum. However, at force levels above this value, variability decreased. The motor-output variability predictions were modified to account for the inverted-U shaped function that Schmidt and Sherwood also then found for movement accuracy.

Thus, the variability of force as a function of force has been claimed to be a square root function (Fullerton & Cattell, 1892), a nonproportional but increasing function (Jenkins, 1947), a linear function (Schmidt et al., 1979) and an inverted-U shaped function (Sherwood & Schmidt, 1980). There are a number of experimental factors that could influence estimates of force variability as a function of force produced. Among these may be transfer effects (Poulton, 1973), insufficient force levels to adequately describe the function and insufficient data points at each force level to obtain a veridical estimate of variability (Fisher, 1915). One potential reason for the discrepancies reported may be that individual subjects varied the time with which they generated the force in a systematic manner. To test this assumption, Newell and Carlton (1984) tested subjects using an elbow flexion task. In absolute terms, force variability increased but at a decreasing rate in a manner similar to that reported by Fullerton and Cattell. However, it appeared that this was accomplished by increasing time to peak force as the required force level increased. This suggests that subjects are able to change rate of force production according to the criterion force required. Therefore future investigations of isometric force production tasks need to consider the individual freely chosen rate of production as an important variant.

ISOTONIC TASKS

In isotonic tasks the goal of the act is often based on spatial and temporal criteria. Investigations of isotonic contractions have focused on control parameters such as spring stiffness, viscous damping and inertia which affect the work required by the task and as has been presumed the kinesthetic feedback associated with response (Bahrck, 1957). In this work emphasis has been laid on the use of spring centered controls which allow for the simultaneous presentation of both distance and force cues. As force production is proportional to movement distance in these systems, force variability may be measured by distance variability and this has generally been the experimental tactic adopted. Although this confounding of distance and force parameters produces several interpretational problems, these studies do provide useful insights into factors affecting output variability.

Although the early studies of Weiss (1954) suggested that force cues were not beneficial in dynamic responses, possibly as they provided only redundant information, a number of subsequent works have indicated the efficacy of such cues in improving spatial accuracy in positioning responses (Bahrck, Bennett, & Fitts, 1955; Gibbs, 1954; Howland & Noble, 1953). Bahrck, Bennett and Fitts (1955) is representative of this work. They examined the accuracy of positioning

responses under constant spring tension, where tension increased with change in position of the control stick. It was proposed that this protocol allowed for an evaluation of cues associated with amplitude, terminal torque and rate of change of torque with amplitude. The authors concluded that indeed each of these factors were important in governing positioning errors but that error was minimized when the ratio of relative torque change to displacement was maximized, particularly if this coincided with a large absolute change in torque with displacement. However, as Bahrick and his colleagues used absolute rather than variable error it is difficult to contrast their results directly with those for isometric force production.

With the advent of the motor-output variability model, there have been a variety of contemporary studies which have examined the force variability function in isotonic tasks. The basic tenet of the model is that there is a proportional relationship between the size of the impulse produced and its variability. As support for this proposal, Schmidt and his colleagues produced data upon both discrete and reciprocal aiming movements and rapid timing responses. Their results indicated that the within-subject variability of impulse duration increased linearly with movement time. Also, there were no interactional effects between movement time and amplitude for the variability of impulse duration. As was indicated this affirmation leads to estimates of proportional relations between movement error and movement speed. Although Schmidt et al presented some data in support of such a position there is a substantial body of research that variable error increases at a negatively accelerating rate for constant increments of movement speed with a given movement amplitude (e.g., Fitts, 1954; Woodworth, 1899) and that variable timing error decreases at a negatively accelerating rate with constant increments of amplitude within a given movement time (Newell, 1980). The above represents only a short precis of a rather more complex picture of which much fuller details appear in Hancock and Newell (1984).

The prediction of the motor-output variability model that spatial errors increase proportionally with movement distance whereas movement timing error remains unaffected is based upon the assumption that absolute impulse varies with amplitude. For the case where double the amplitude is covered, double the impulse is required which doubles spatial error. However, because in this situation the movement is being generated twice as fast timing error is unaffected. Also, a proportional relation would require that the addition of mass to the movement system have no effect on spatial or temporal accuracy. This is because the addition of mass has two equal and opposing effects. First, it increases the variability of the motor system due to a larger impulse being produced but second, it increases the inertia of the system which provides resistance to variability in the movement. Therefore, if the relation between impulse and impulse variability were proportional, there should be no effect on timing accuracy when movement distance or when movement mass is varied. Recent studies by Newell and his colleagues have indicated that neither of these observations is born out in experimental data and therefore suggest that the force/force variability function is not a simple proportional relationship.

Taken collectively, the studies for isotonic tasks do not present as coherent a picture as those for isometric performance and this may be due to the variety of manipulations, e.g., spring centered controls, employed. However, in conditions which do not change throughout the force production continuum, a curvilinear function compatible with that observed in isometric tasks has been reported (e.g., Newell, Carlton, & Carlton, 1982). This overall function is also compatible with previous descriptions of kinematic variation (Hancock & Newell, 1984).

FORCE VARIABILITY AND MODELS OF RESPONSE PRODUCTION

The present synthesis of the relation between force and force variability in both isometric and isotonic tasks suggests that a negatively accelerating rate of force variability is produced when equal increments of force are manipulated across the continuum available to the performer. This function is consistent with our space-time analysis of the movement speed accuracy relationship although we have yet to formalize a link between the kinematic and kinetic components of response variability (Hancock & Newell, 1984). Schmidt et al. (1979) made explicit and presented an attempt toward this link which has been implicit in movement studies since the earliest investigations (Fullerton & Cattell, 1892). However, certain predictions derived from the model of Schmidt and his colleagues have not been affirmed by experimental data and a full description of the kinematic-kinetic link awaits further development.

The current kinetic analysis of response variability reveals several limitations to extant models of force production. Subjects apparently minimize response variability by modulating the rate of force production for a given set of isometric or isotonic task constraints. In isometric tasks, subjects do not scale-up peak force by holding time to peak force constant as postulated explicitly by pulse-step (Ghez & Vicario, 1978) and implicitly by motor-output variability (Schmidt et al., 1979) models. Rather, they systematically vary the time to peak force according to task constraints (Danoff, 1978; Newell et al., 1982). The basis for this variation is at present unclear, however, it appears consistent with principles of efficiency in muscular contraction, where efficiency is defined as the ratio of the work done to the energy expended.

In pioneering work, Hill (1922) investigated the speed of muscular contraction with respect to its relationship to mechanical efficiency in human skeletal muscle. He suggested that the rate of contraction is the key parameter in determining this mechanical efficiency. Further, he observed a nonlinear relation between efficiency losses in muscular contraction and the deviation from the optimal contraction duration. Efficiency has since been invoked as an emergent property of the optimizing motor system (e.g., Sparrow, 1983). However, a formal link between notions of variability and efficiency has not yet been realized. It is conjectured that following practice, an individual's freely chosen rate of force production is optimal for the efficiency of muscular contraction.

Efficiency is an attractive avenue to pursue, not only because of its theoretical appeal but because it can encapsulate arguments that may be advanced concerning the role of specific physiological mechanisms, such as motor unit recruitment, within the variability function (Hatze & Buys, 1977). Efficiency principles also suggest that the coordination and control of human movement cannot be understood from purely mechanical principles alone. Although this position has gained acceptance in research on biomechanical optimization, this perspective has yet to be fully developed by those seeking to understand processes of movement production. Efficiency of muscle mechanics is consistent with a peripheral hypothesis regarding response variability but central mechanisms may also affect force production. One premise of the motor-output variability model is that repeated responses enable the "same" motor program and thus minimizes centrally mediated response variability. However, and in accord with Schmidt and his colleagues, we would not suggest that this means no effect for supposed central processes. Indeed, our synthesis suggests that central mechanisms may well contribute to the force variability function. Whether central mechanisms can also be related to efficiency in discrete responses as it can in gait (e.g., Bolis, Schmidt-Neilson, & Madrell, 1973) awaits development.

Efficiency could be a principle that specifies a priori a particular biokinematic organization of the organism and constrains the interaction of central and peripheral contributions in the coordination and control of movement (e.g., Sparrow, 1983). The implication of an efficiency orientation to motor control is that response variability will reflect the degree to which task and environmental constraints demand deviation from organismically optimal kinematics and kinetics.

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