IS MOVEMENT VARIABILITY IMPORTANT FOR SPORTS BIOMECHANISTS?

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This review paper addresses the importance for sports biomechanics of movement variability, which has been studied for some time by cognitive and ecological motor skills specialists but largely overlooked by sports biomechanics. The paper considers biomechanics research that shows EMG variability, inter- and intra-individual kinematic variability, and computer predictions of movement variability. The paper concludes by recommending that sports biomechanists should focus more of their research on movement variability and on important related topics, such as control and coordination of movement, and implications for practice and skill learning.

KEY WORDS: constraints, coordination, movement control, multi-disciplinarity, variability

INTRODUCTION: In my keynote address to the ISB in 1995, I highlighted three broad topics upon which I considered future sports biomechanics research should focus:
- Coordination-control of movement to understand sports performance better.
- Estimation of tissue loads to give greater insight into how to reduce injury risk.
- Research into the use of biomechanical feedback and interventions to improve performance and reduce injury risk.

Although the lecture and the resulting position paper (Bartlett, 1997) were, apparently, well received, on reflection I ask myself, 'What did I get wrong?', or, to generalise, 'What has sports biomechanics got wrong?' This raises two sub-questions. First, what was implicitly assumed in my lecture and, perhaps, by sports biomechanists in general? Possibly:
- Motor invariance.
- Optimal motor patterns or movement techniques.
- A hierarchical approach (are all sports biomechanists logical positivists?)

Secondly, what was missing from my lecture and, perhaps, from our world picture?
- Intra-individual studies - there have been far too few of these in our discipline.
- Acknowledgement that the use of discrete variables imposes severe limitations and that we should have put more emphasis on time-series analysis, particularly as nearly all our data acquisition techniques provide time-series data, e.g. motion analysis, forces, EMGs.
- And last, but by no means least, variability.

What follows is a personal reflection, not an extensive review of the research of others, except to contextualise. I will discuss, briefly, some of the work of my various research colleagues, with supportive examples from other literature, in:
- Variability in EMG patterns.
- Kinematic variability between elite throwers.
- Kinematic variability within throwers.
- Computer simulations that seem to predict variability.

I will then assess what I believe this means for sports biomechanics. Many sports biomechanists, me included, have - explicitly or implicitly - made assumptions that research in movement variability seriously questions.

VARIABILITY IN EMG: Grieve (1975) presented 6 EMG records taken from the same person on the same electrode site on the hamstrings from six successive strides in constant speed treadmill running. You cannot get a much more stereotyped activity. Yet, although the EMGs were very similar, they were by no means identical and point to variable motor unit recruitment. Other studies have strongly supported this EMG variability. For example, Miller (2000) reported variability in EMGs from arm and leg muscles in the basketball free throw. Such EMG variability raises questions, for example, 'Is this a recruitment strategy by the neuromuscular control system?' The answer to such a question would require input not only from biomechanists but also from motor skills specialists with relevant expertise.

INTER-INDIVIDUAL KINEMATIC VARIABILITY: Morris, Bartlett, & Fowler (2000) reported the results of a study of the three men's javelin medallists in the 1995 World Athletics Championships, with a focus on arm contributions to release speed.
- One used predominantly humeral medial rotation.
- One used predominantly elbow extension.
- One used predominantly shoulder extension-horizontal flexion.

Such differences hardly lend support to the idea of a common optimal motor pattern or technique, and question the approach of trying to copy the most successful performers. Further evidence to this effect has been provided, for example, from self-organising Kohonen maps for javelin and discus throwing by Schollhorn & Bauer (1998).

INTRA-INDIVIDUAL KINEMATIC VARIABILITY: We have also reported kinematic variability in, for example:
- Elite javelin throwers; Morriss, Bennett, Bartlett, Komi, Worrall, & Payton (2004, in press) studied four throws, all for maximum range, from the men's Gold medallist at the 1996 Olympic Games, and presented the results as cross correlation coefficients. The cross-correlations between the right shoulder and elbow joint angles, for example, which had a relationship close to linear, showed very similar patterns for rounds 2 and 6, and for rounds 4 and 5, almost within the limits of experimental error. The same was not true between the 2-6 and 4-5 pairs, which had substantial amplitude and phase differences.
- Novice, club and elite javelin throwers (Bartlett, Müller, Lindinger, Brunner, & Morriss, 1996). Although not reported explicitly in that paper, intra-individual differences were greater for the novice and the elite throwers than for the club throwers.
- Skilled basketball free throws (Miller, 2000). Such variability has also been reported by Button, MacLeod, Sanders, & Coleman (2003).

None of this research supports the concepts of intra-individual movement consistency or motor invariance. Even elite athletes appear unable to produce invariant movement patterns after years of practice (Davids, Araújo, Glazier, & Bartlett, 2003).

COMPUTER PREDICTIONS OF MOVEMENT VARIABILITY: An interesting computer simulation that predicted movement variability was the much-cited paper by the late Herbert Hatze (1976). Participants, wearing a weighted boot, had to hit a target using only hip flexion and knee extension. The real motions were compared using transentropy scores - later proposed by Hatze (1995) as a better measure of variability than standard deviation or coefficient of variation - with computer predicted optimal performances for that person, based on personalised models of the lower limb muscles and segment inertia parameters. Aside from the interesting information on knowledge of results from this study:
- The best real and computer optimum motions were very similar, but this was not the case for the muscle activation patterns.
- Kinematically identical computer optimisations resulted from substantially different activation patterns.
- These results can be interpreted as meaning that even optimal motions could be caused by variable muscle activation patterns, a computer prediction of variability even in optimal movements.

A second prediction of variability in sports movements was seen in Best, Bartlett, & Sawyer (1995), who presented their results as contour maps of two variables, for example, the release angle of attack of the javelin against release angle, with other release parameters kept constant, as it is difficult to represent n-dimensional space in two dimensions. The contour lines were lines of equal distance thrown. The peak of the 'hill' represented the maximum distance that a given thrower could throw a particular make of javelin. It should be noted that:
- Only one combination of release parameters gave the maximum throw.
- On any two-dimensional contour map, any pair of release parameters on a constant range line will produce that sub-optimal throw, even when the sub-optimal range is only slightly less than maximal; this generalises to n-dimensional representations of the release parameters. These

results show than infinite combinations of release parameters will result in the same sub-optimal range; each of these combinations could have arisen from kinematically different movements of the thrower.
- Furthermore, the unique maximal throw combination of release parameters could also have arisen from kinematically different motions that generated the optimal release parameter values.

CAUSES OF MOVEMENT VARIABILITY: I do not have the expertise to discuss movement variability from a motor control viewpoint, but, as we know, different motor control paradigms have different views. The cognitive school considers variability as undesirable system noise (error), and sees variability as reducing with skill learning as the learner controls unwanted degrees of freedom in the kinetic chain. Ecological motor control views variability as having a functional role in human movement. Variability is seen as functionally essential in inducing a coordination change and it gives flexibility to adapt functionally to changes in the environment. This motor control group sees skill learning and practice as an exploration of the perceptual-motor workspace (see, e.g. Handford, Davids, Bennett, and Button, 1997).
Sports biomechanists have not, until recently, shown enough interest in movement variability. Several sports biomechanics research groups, such as that at Sheffield Hallam University in the UK and Joe Hamill and his colleagues at the University of Massachusetts in the USA, have already started to rectify this omission, but we have a long way to go to catch up with the decades-long interest in this topic by motor skills specialists. What can sports biomechanists contribute to the study of movement variability?
- First, a third possible functional role of variability (see, e.g., Heiderscheit, Hamill, & van Emmerik, 1999). If movements were repeated identically, it is more likely that the same tissues would be maximally loaded each time. Adding in kinematic variability would probably modify tissue loads from repetition to repetition, reducing injury risk.
- Secondly, insight into variability in multi-segment movements. Single-segment or single degree-of-freedom movements have dominated those investigated by the cognitive school of motor control, and much of the early work of the ecological school - although the latter have turned their attention to real-world tasks, such as sport. In contrast to these simple movements, in multi-segmental ones, inertial coupling probably causes variability 'transfer' between segments; furthermore, muscles contribute to forces and moments at joints other than those they span, further complicating our understanding of movement variability.
- Thirdly, another view in the multi-disciplinary effort to understand movement control and coordination and the role of variability within that.
- Fourthly, other approaches, such as neural nets, which I've already touched on.
- Lastly, other examples of variability, as exemplified above.

FUTURE DIRECTIONS FOR SPORTS BIOMECHANICS: I wrote above that many sports biomechanists have made assumptions, which research in movement variability seriously questions. We should accept that movement variability is crucially important for sports biomechanics and address the challenges it poses. So, how should sports biomechanics respond to the issues raised by movement variability, as well as the related topics of movement control and coordination, and the implications for practice and skill learning?
- We should carry out more collaborative research with specialists in motor control, motor learning and motor development, into the control and coordination of sports movements.
- We need multidisciplinary studies of skills that need adaptation to environmental or task constraints, or that pose a threat of injury - an organismic constraint, or none of these, to tease out the relative importance of various sources of noise and functionality in movement variability. We have recently started such a collaborative project between my University and the University of Otago.
- We should place far more emphasis in sports biomechanics on intra-individual studies, generally as multiple single-individual designs, to address issues such as individual 'signatures' of movement coordination and optimisation of performance, rather than group designs that

obscure important information. We also need to convince journal editors of the importance of such designs; the editor of Sports Biomechanics is already on board!

To continue, but with more of a focus on injury mechanisms - in which, again, intra-individual studies are vital - we need:

- Studies of other sports movements, in addition to running, to establish if variability in segment coordination might indicate a function to prevent injury.
- Longitudinal studies of specific sports movements to see if individuals with low movement variability sustain more or less injuries that those with high variability. We also need to study how injury affects variability in the post-injury, treatment and rehabilitation phases.
- Lastly, and semi-philosophically, we need to investigate whether movement variability functions as some kind of 'inverse optimisation' function for groups of, or all, sport and exercise movements. I'm not yet sure how we would do this, but it is worth noting that optimisation cost functions without variability have been spectacularly unsuccessful in partitioning loads between muscles in a physiologically meaningful way.

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