Is Movement Variability Important for Sports Biomechanists?

Running title: Importance of movement variability in sport

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ABSTRACT

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, until quite recently, had largely been overlooked by sports biomechanists. The paper considers biomechanics research reporting inter- and intra-individual movement variability in javelin throwing, basketball shooting and running. We conclude 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.

INTRODUCTION

In a keynote address to the International Society of Biomechanics in 1995, the speaker highlighted three broad topics upon which he 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.

With the wisdom of hindsight, the resulting position paper (Bartlett, 1997) raises at least two questions. First, what was implicitly assumed in that paper? Certainly, one could argue: motor invariance, the existence of optimal motor patterns or movement techniques, and the validity of representative trials. Secondly, what was missing from that overview? Indeed, any consideration of the use of intra-individual studies, of which there have been far too few in our discipline. There was no 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. Last, but by no means least, the importance of movement variability was neglected (Bartlett, 2004).

What follows is a review of biomechanics research into movement variability, focused around throwing skills in track and field athletics and basketball, and running. We start with some research by Bartlett and his colleagues into javelin throwing, which reported variability - even though that was not necessarily the main focus - between elite throwers and within throwers, and from computer simulations that seemed to predict variability. We then move on to research into variability in basketball shooting and running. We conclude by outlining what we believe movement variability means for sports biomechanists and for practitioners. Throughout this review, we use the term movement variability – or simply variability – for all variables in which variability is found, irrespective of whether these are movement or coordination variables. This review does not cover in depth the theoretical background to movement variability, which would be inappropriate for this journal, although we introduce some important theoretical ideas, particularly in the section on running (see also Glazier *et al.*, 2006). Neither is the focus of this review on how movement coordination and variability are measured; these topics have been extensively and recently addressed elsewhere (see, for example, James, 2004; Wheat and Glazier, 2006).

VARIABILITY IN JAVELIN THROWING

Similarly to the examples of basketball shooting and running in the following two sections, research into javelin throwing, and the other throws in athletics, has rarely focused on movement variability. Morriss *et al.* (1997) reported the results of a study of the men's javelin final in the 1995 World Athletics Championships, with a focus on arm contributions to release speed. The very large shoulder angular velocity for the silver medallist suggested a reliance on shoulder horizontal flexion and extension to accelerate the javelin, which would suit his linear throwing style. In contrast, the gold medallist used medial rotation of the shoulder as a major method of accelerating the javelin, this movement, combined with an elbow extension angular velocity that was at least 18% larger than for any other of the 12 finalists, is the reason why he was able to achieve the greatest release speed. The other finalists also used various combinations of these three arm movements to generate release speed. Such differences between throwers hardly support the idea of a common optimal motor pattern or technique, and question the approach of trying to copy the most successful performers. These differences are the result of the individual-specific self-organisation process (see Clark, 1995) such that performers find unique solutions to a task.

Morriss *et al.* (1997) considered that these differences in the movements of the upper arm and forearm between throwers have important implications for their physical training. The training exercises performed by each thrower should be done in a way that replicates their individual movement patterns such that the gold medallist, for example, when ball throwing should emphasise shoulder medial rotation and elbow extension to ensure movement specificity (Enoka, 1994).

Further evidence to this effect has been provided, for example, from self-organising Kohonen maps for javelin throwing by Schöllhorn and Bauer (1998) and for discus throwing by Bauer and Schöllhorn (1997). Because of the greater clarity of the presentation of the results of their discus study, we have included it in this section. They used 53 throws (45 of a decathlete, 8 of a specialist) recorded using semi-automated marker tracking over a one-year training period. There were 34 kinematic time series for each throw, for 51 normalised times; these complex, multi-dimensional time series were mapped on to a simple 11 x 11 neuron output space (Figure 1). Each sequence was then expressed as the mean deviation (*d* in the figure) of the output map – the continuous line - from the output map of one of the throws by the specialist thrower, shown by the dashed line.

****Figures 1 and 2 near here****

The deviations for the eight specialist throws are shown on the right of Figure 2 and the decathlete's 45 throws on the left. The 'distances' are less for the specialist thrower as the comparator was one of his throws. Note the clustering of groups of throws, between the grey or black vertical lines, within training or competition sessions. There was more variability between than within sessions - for five groups of five trials, the authors computed inter- and intra-cluster variances, giving an inter-to-intra variance ratio of 3.3 ± 0.6. This shows that even elite throwers cannot reproduce invariant movement patterns between sessions. The supposed existence of such invariant patterns – which arose mainly from the motor program concept of cognitive motor control - has often been used, explicitly or implicitly, to justify the use of a 'representative trial' in sports biomechanics; such trials clearly do not exist.

Schöllhorn and Bauer (1998) reported a similar approach to analyse 49 javelin throws from eight elite males, nine elite females and ten heptathletes. This time, manual digitising of estimated joint centre locations was used. Clustering (shown in the blue ringed areas) was found for the male throwers – as a group - and for the two females for whom multiple trials were recorded (Figure 3). Variations in the cluster for international male athletes were held again to contradict any existence of an 'optimal movement pattern'.

****Figure 3 near here****

Intra-individual movement variability was reported for elite throwers by Morriss *et al.*

(2005, in press). They 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 of the throwing arm (Figure 4), for example, showed very similar patterns for rounds 2 and 6, and for rounds 4 and 5, within the limits of experimental error, as outlined below. The same was not true between the 2-6 and 4-5 pairs, which had substantial amplitude and phase differences (Figure 4). Bartlett *et al*. (1996) reported intra-individual differences in novice, club and elite javelin throwers; although not reported explicitly in that paper, intra-individual differences were greater for the novice and the elite throwers than for the club throwers. Even throwers striving for maximum distance cannot generate identical coordination patterns.

****Figure 4 near here****

In the context of some of the above studies (Schöllhorn and Bauer, 1998; Morriss *et al.*, 1997; 2005), the results of a study by Bartlett *et al.* (In Review) merit attention. They reported the results of a study of five trials of treadmill running in a laboratory to ascertain the reliability of manual digitising of body coordinates with and without markers; four experienced operators digitised the trails on each of five consecutive days, with the no-markers trials being digitised before the ones with markers, to inhibit learning of marker positions. In the marker trails, the reliability intra- and inter-operator was good (Figure 5a, b), with the former similar to autotracking; movement (trial-to-trial variability) dominated the other sources of variance. However, this was not true for the no-markers condition (Figure 5c, d), in which movement variability was often swamped by the other sources of variance. The authors concluded that movement variability could not be determined reliably without the use of markers and speculated that this would be even worse for three-dimensional studies in competition in which the positions of some ‘joint centres’ have to be estimated from invisible landmarks. It is with those results in mind that the four trials in the study of Morriss *et al*. (2005, in press) have been divided into two pairs – the differences within each pair would fall inside the limits of such experimental errors.

****Figure 5 near here****

A computer simulation model that predicted variability in sports movements was seen in Best *et al.* (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 (Figure 6), as it is difficult to represent *n*-dimensional space in two dimensions. The contour lines are lines of equal distance thrown. The peak of the 'hill', shown by a star, represents 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. However, 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, as for contour line 29 on Figure 6 indicated by the arrow; 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 (see Kudo *et al.*, 2000). Outcome consistency does not require movement consistency.

****Figure 6 near here****

These computer simulation results predict ‘sub-optimal’ movement variability. This variability in javelin throwing could be functional in allowing adaptations to environmental changes, such as wind conditions, or to distribute maximal loads on each throw among different tissues, both of which are discussed further below in the section on running.

VARIABILITY IN BASKETBALL SHOOTING

Shooting is the most important skill in the sport of basketball and many researchers have, consequently, studied this aspect of the game. Changes in basketball shooting kinematics have been examined either as a function of distance (Elliott and White, 1989; Miller and Bartlett, 1996; Miller, 2002; Robins et al., in review), gender (Elliott, 1992), ability (Penrose and Blanksby, 1976; Hudson, 1985; Button et al., 2003) or shooting accuracy (Miller, 1998). One of the general trends to emerge is that shooting is a compromise between the allowable margin for error and energy expenditure (see Miller and Bartlett, 1996). The joint configurations and release parameters used by players are, therefore, tailored to a particular shooting distance. For example, players use a shallower shooting trajectory at greater distances to reduce the required ball release speed (the minimum speed principle, see Miller and Bartlett 1996). However, this produces a correspondingly lower margin for error.

Movement variability in basketball shooting has received little attention until recently (Miller, 2002; Button *et al*., 2003; Robins et al., in review). Miller (1998, 2002) reported variability in discrete variables for five successful and five not-deliberately unsuccessful free throws from the free-throw line and five successful ones from a shorter and a longer distance, for 12 experienced players. He reported no evidence that the players could generate identical movements from shot to shot. There was increased absolute variability, expressed as standard deviation, in segment end-point speeds, from the longest to the shortest distances, which was reversed for relative variability, expressed by the coefficient of variation (Figure 7). No significant difference in absolute variability of joint position at release was found between successful and unsuccessful throws. For instance, the standard deviation for range of motion (°) in free throws for the wrist and elbow joints was 7.5 and 6.3 for accurate shots and 7.5 and 5.7 for inaccurate shots. An increasing trend in absolute variability of segment end-point speed along the segment chain was also apparent, but a deceasing trend in relative variability (Figure 7).

****Figure 7 near here****

Button *et al*. (2003) examined how movement variability in the basketball free-throw was affected by differing abilities among female players ranging from a senior national team captain and two under 18 national team players to a player of very little experience. Skilled performers were characterized by increased inter-trial consistency from the elbow and wrist joints, but no clear reduction in trajectory variability occurred as skill increased. Compensatory variability was also demonstrated by the elbow and wrist to minimise the variability of the release parameters. The skilled players used a greater range of wrist motion but the authors did not allude to the potential importance of this finding from a coaching perspective.

Robins and his co-workers (Robins, 2003; Robins *et al.*, in review) analysed five successful jump shots from each of six experienced players from the free-throw line and two further distances. Their findings suggested that all participants were capable of replicating the desired movement pattern at all three distances, and showed a narrow bandwidth of movement variability (see Figure 8). This narrow bandwidth of movement variability corroborates earlier research demonstrating a reduction in movement variability with practice in basketball (Button *et al*., 2003) and dart throwing (McDonald *et al*., 1989). However, for the discrete variables examined, there was a sequential increase in movement variability, with variability increasing proximally along the kinematic chain at release. This agrees with the above findings of Miller (2002) of an increasing trend in absolute variability of segment end-point speed along the segment chain. The results of the studies of Miller (2002) and Robins (2003) are not surprising considering the significant increase ($p < 0.05$) in maximum end-point speeds of the shoulder, elbow, wrist and fingers with distance reported by Elliott (1992).

****Figure 8 near here****

However, Robins (2003) found that the movement variability at the shoulder and elbow did not increase as a function of distance; the wrist was the only joint with an increased variability of joint position at release. Furthermore, the variability of joint angles at release did not adversely affect the height, angle or speed of release, suggesting that compensatory mechanisms were present at the wrist and elbow joints to ensure invariant release parameters, and implying a more functional role for movement variability. This might explain why the height of release remained stable because, for example, a reduction in shoulder extension could be corrected for by increased elbow extension. A lower height of release would have the adverse effect of requiring a greater speed of release for a given release angle (Miller and Bartlett, 1993). Therefore, compensation between the shoulder and elbow is beneficial as it allows the maintenance of a given release height, thereby maximizing the chance of success. These findings support other literature on compensatory variability in basketball shooting (Button *et al*., 2003).

A significant reduction in variability with distance was also found by Robins (2003) for continuous relative phase for the joint couplings of the wrist-elbow (p = 0.01) and wrist-shoulder (p = 0.01). Reductions in variability were greater for continuous relative phase, but this is arguably a consequence of the increased sensitivity of this measure to changes in coordination, as it includes the joint angular displacements and velocities from the two joints. The decrease in both discrete and continuous measures of movement variability with distance can be attributed to the reduction in margin for error. A smaller margin for error at longer shooting distances requires a more constrained movement pattern, one that is characterized by lower movement variability. Therefore, the magnitude of variability is dependant upon the constraints of the task (Newell and Vaillancourt, 2001).

The availability of equally functional movement patterns is important because it offers greater flexibility to adapt to potential perturbations and environmental uncertainty.

This is particularly important during basketball competition because the extent of defender interference or pressure increases as players move closer to the basket. However, this flexibility is not available at greater distances, because the margin for error demands that the coordination pattern is more closely constrained. Coaches are therefore advised to devise strategies and play patterns that provide free scoring opportunities when shooting from the perimeter. This will minimize defender interference and prevent the shooter from having to manipulate his or her technique to any great extent. The results of Robins (2003) demonstrated a reduction in continuous coordination variability for the joint couplings of the wrist-elbow (p = 0.01) and wrist-shoulder (p = 0.01), despite an increase in range of motion at the wrist (p = 0.0001). A large range of motion at the wrist was also observed by Button *et al*. (2003), who found that skilled performers displayed more than twice the wrist flexion (82°) of any other performer. An increase in wrist amplitude may serve several purposes. First, a larger range of motion at the wrist may be used in conjunction with an increase in vertical and horizontal displacement of the jump (Elliott, 1992) to assist with impulse generation. Secondly, exploring a fuller range of motion may enable a more effective compensatory mechanism to ensure end-point accuracy.

VARIABILITY IN RUNNING

Sports biomechanists have investigated running mechanics with the aim either of enhancing performance (e.g. Saunders *et al.*, 2004) or, more frequently, of identifying biomechanical factors that might cause overuse injury (e.g. McClay and Manal, 1997; Stergiou *et al.*, 1999; Hreljac e*t al.*, 2000). Traditional approaches to the study of running mechanics have been greatly influenced by theories of the cognitive approach to movement control; consequently, biomechanical studies of running have tended to focus on identifying the invariant properties of human movement. Therefore, biomechanics researchers have consistently assumed that within- and between-runner variability is of little or no importance. Indeed, techniques for reducing and eliminating both within- and between-participants variability have been used frequently (e.g. Hunter *et al.*, 2004; Schwartz *et al.*, 2004; Mullineaux *et al.*, 2004).

Another approach to movement coordination and control is known as based on non-linear dynamical systems theory (Hamill *et al.*, 1999), which is often referred to simply as dynamical systems theory, a practice we will use, although the non-linearity of such systems is crucial to their behaviour. This approach challenges traditional views of movement variability, which assume variability to be system noise or error that must be eliminated: non-linear dynamical systems theory, in contrast, proposes that variability is functional. Hamill *et al.* (1999) stated that a central message of the work in motor control from a dynamical systems perspective (e.g. Schöner *et al.*, 1986) is that variability in movement is necessary for changes in the coordination of movement, for example from walking to running or vice versa (Diedrich and Warren, 1995). As well as assisting in coordination changes, various authors have postulated recently that another function of movement variability might be to attenuate impact shocks when runners are subjected to large forces (Holt *et al.*, 1995; Hamill *et al.*, 1999; Heiderscheit *et al.*, 1999; James *et al.*, 2000; Heiderscheit *et al.*, 2002; James, 2004). These authors suggested that variability in movement might provide a broader distribution of stresses among different tissues, potentially reducing the cumulative load on internal structures of the body. Furthermore, James (2004) recently formulated the 'variability-overuse injury hypothesis' (Figure 9), in support of which some experimental evidence exists (Hamill *et al.*, 1999; James *et al.*, 2000; Heiderscheit *et al.*, 2002). Because of the potential functional roles of movement variability, it would appear that there is a need to re-assess the solely negative views of variability.

****Figure 9 near here****

Traditionally, dependent variables in studies of running biomechanics – as in the biomechanics of throwing skills in the previous two sections - have tended to be discrete data from isolated joints (e.g. Paradisis and Cooke, 2001). However, the dynamical systems approach advocates that the coordination or coupling between joints of the lower extremity is important. Running, like throwing, is a complex motor skill that involves many degrees of freedom. To produce coordinated movement and master the many interacting components in the human body, the runner must solve what Bernstein (1967) termed the 'degrees of freedom problem'. Recently, it has been recognised that analysing discrete variables from isolated joints does not effectively capture the complexity of the coordinated motions of components of the body. An excellent example of this during running is the coordinated actions of the subtalar and knee joints. Briefly, both knee flexion and subtalar eversion promote internal rotation of the tibia. Conversely, subtalar inversion and knee extension promote external rotation of the tibia. Therefore, it has been suggested that a disruption to the coordination between the subtalar and knee joints during the stance phase of running might create torsional stresses on the tibia and abnormal loads on the knee joint (e.g. McClay and Manal, 1997; Stergiou and Bates, 1997; Stergiou *et al.*, 1999; DeLeo *et al.*, 2004). With this in mind, investigating the actions of the subtalar and knee joints in isolation might omit important information about running injury mechanics.

Hamill *et al.* (1999) were among the first to use the dynamical systems approach to investigate overuse running injuries. These authors recognised the two important tenets of dynamical systems theory outlined previously in this section – the importance of movement variability and inter-segment coordination. Using a retrospective research design, they compared the variability in lower extremity coordination of participants with patellofemoral pain with a group of healthy, matched controls. Less variability was reported for the patellofemoral pain group than the control group (Hamill *et al.*, 1999). Potentially, these results provide support for the hypothesised link between variability and overuse injury. Follow-up studies (Heiderschiet, 2000; Heiderschiet *et al.*, 2002) reported similar results to Hamill *et al.* (1999). However, with the retrospective research designs used in these studies, it is impossible to determine whether the decreased variability was the cause or the effect of the patellofemoral pain. In addition to the possibility that lower variability caused the injury, it is just as plausible that the decreased variability seen in the injured participants was the result of pain (*c.f.* Hamill *et al.*, 1999; Heiderschiet, 2000; Heiderschiet *et al.*, 2002). Hamill *et al.* (1999) suggested that the decreased variability seen in the patellofemoral pain group could have been a result of the participants constraining their movements within tight boundaries inside which pain was reduced. Heiderscheit (2000) presented preliminary findings that provide support for this notion; he monitored variability in coordination after reduction in pain due to the application of patella taping. He found that variability in the coordination patterns in the injured group increased to near that of the healthy group after reduction in pain.

The findings of Hamill *et al.* (1999), Heiderschiet (2000), and Heiderschiet *et al.* (2002), together with the results presented by James *et al.* (2000), have demonstrated a potential relationship between coordination variability and overuse injury. As many authors have highlighted, more work is required to determine whether the decreased variability seen in injured participants is the cause or the effect of the injury. Specifically, work is required to confirm or refute the variability-overuse injury hypothesis presented by James (2004).

A third functional role for movement variability is that of facilitating adaptation to changes in the environment, as previously mentioned for javelin throwing. Wheat and his colleagues (Wheat *et al.*, 2003; 2004; 2005; Wheat, 2005) have reported comparisons of running overground, on a standard treadmill and on an on-demand treadmill, in which the belt speed adapts to the speed of the runner (Minetti *et al*., 2003).

****Figure 10 near here****

Between the overground and treadmill conditions, for 13 male runners, they reported significantly reduced variability in lower extremity coordination ($p < 0.05$) on the treadmill for all joint couplings studied over the entire stride and in various phases of the stride cycle (Figure 10). These results were in agreement with data on the variability in the vertical velocity of the centre of mass during running (Wank *et al*., 1998). The results also lent some support to the hypothesis of Holt *et al*. (1995) that variability in coordination patterns might provide an adaptive mechanism to potential external perturbations, such as uneven ground. However, as Wheat (2005) noted, the reduced variability in treadmill running could have other causes. Potential reasons for the differences include, for example, intra-stride belt speed variations, changes in air resistance, changes in perception of the threat of an external perturbation, changes in optical flow information and the artificially constant speed of the treadmill belt. Whether the reasons for the differences in variability between the two modes of locomotion are related to changes in the mechanical constraints, perceptual information or any other factors, there are important implications, such as the possibility that the reduced variability in treadmill running will result in an increased risk of overuse injury.

In their second study, the treadmill-on-demand, for which the treadmill speed is not constant, was added to the overground and treadmill conditions (Wheat, 2005; Wheat *et al*., 2005). The differences in coordination patterns between the two treadmill conditions (Figures 11 and 12) for 11 male runners were not statistically significant; furthermore, the differences between overground and treadmill, and overground and treadmill-on-demand running were similar (effect sizes, respectively, 0.84-1.71 and 0.94-1.95). The constant speed of the treadmill belt on a conventional treadmill does not appear, therefore, to account for the reductions in variability observed between treadmill and overground conditions. It is not, at present, clear which other factors are responsible for the differences. We would speculate that the suggestion of Holt *et al*. (1995) of an adaptive mechanism to potential external perturbations, of which there is a lesser threat on a treadmill, and the reduction of optical flow information on a treadmill are strong candidates to explain the differences between treadmill and overground movement variabilities.

****Figures 11 and 12 near here****

SUMMARY AND IMPLICATIONS

None of the research discussed above 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 *et al.*, 2003). Such research also militates against the concepts of inter-individual optimal movement patterns and 'representative' trials. It also argues very strongly for within-individual studies to supplement, or replace in some cases, group designs.

Different motor control paradigms have different views of variability. Cognitive motor control theorists traditionally considered variability as undesirable system noise, or error, and saw variability as reducing with skill learning as the learner freezes unwanted degrees of freedom in the kinematic chain. Ecological motor control specialists view 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 effectively 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 *et al*., 1997).

Sports biomechanists have not, until recently, shown enough interest in movement variability. Several sports biomechanics research groups, as noted above, have already started to rectify this omission. What this involvement has already added to existing knowledge is a third possible functional role for variability. If movements were repeated identically, it is more likely that the same tissues would be maximally loaded each time. Adding in movement variability probably modifies tissue loads from repetition to repetition, reducing injury risk. This remains hypothetical at present.

Sports biomechanists should also be able to provide a greater 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 both have turned their attention to real-world tasks, such as sport. In contrast to these simple movements, in multi-segmental ones, inertial coupling (Putnam, 1983) might cause 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.

Sports biomechanists are increasingly participating in the multi-disciplinary effort to understand movement control and coordination and the role of variability within that. One potential avenue that still requires exploration is that of artificial neural networks. One advantage of relative phase is that it can compress the velocities and displacements of two joints into a single variable – a reduction of kinematic complexity. Although this can enormously help the study of two-joint coordination, much complexity remains. Artificial neural nets can map very many input time series onto a simple output matrix; however, the uses of this in studying movement coordination and variability are still largely unresearched.

Many sports biomechanists, the lead author certainly among them, 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 require 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 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 need injury-focused studies of other sports movements, in addition to running, to establish if variability in segment coordination might indicate a function to prevent injury.
- We need 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.

And, finally, if movement variability is ubiquitous across sports, as we have shown in this review for javelin throwing, a speed-dominated skill, basketball shooting, in which there is a speed-accuracy trade-off, and running, a cyclic movement pattern, and across stages of skill acquisition, what does this imply for the sports practitioner? This is, perhaps, a question to be directed more at motor skills specialists than biomechanists, but we offer some views based on the research reviewed above.

- As different athletes perform the same task, such as a javelin throw, in different ways, there is no optimal movement pattern to achieve that task for athletes as a whole. Therefore, it makes no sense to try to copy a successful athlete's technique.
- These differences in movements between athletes have important implications for their physical training. The training exercises performed by each athlete should be done in a way that replicates their individual movement patterns, to ensure movement specificity.
- Because athletes do not replicate a movement exactly from trial to trial, for example in basketball shooting, then the use of many trials in training needs to be carefully weighed against potential risks of overuse injury, particularly in activities in which loads on tissues are large, as in javelin throwing.
- As there is no unique movement that optimises the performance of a given sports task, it makes much sense to allow athletes, particularly in the early stages of learning, to explore possible solutions, rather then for the coach to impose too many unnecessary constraints upon them.
- We mentioned in the section on basketball that the availability of equally functional outcomes is important because it offers greater flexibility to adapt to environmental

uncertainty. This is clearly important in competition in many invasive team sports, because the defender interference or pressure often increases as players move closer to the 'target', be that the goal, try line, basket or whatever. However, this flexibility is not available at greater distances, because the margin for error demands that the coordination pattern is more closely constrained. Coaches are therefore advised to devise training strategies and play patterns that provide free scoring opportunities from different distances from the target.

- Because of the reduced variability in treadmill running compared with overground, which will result in an increased risk of overuse injury on the treadmill, care should be exercised in using treadmill running in training or rehabilitation.

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FIGURE CAPTIONS

Figure 1 Mapping of input times series (on left) onto an 11 x 11 output matrix for the discus throw to be assessed (solid line) against the reference throw from the specialist thrower (adapted from Bauer and Schöllhorn, 1997).

Figure 2 Values of *d* for various throws show grouping within training or competition sessions, between the grey and black vertical lines (adapted from Bauer and Schöllhorn, 1997).

Figure 3 Similar to figure 2, but for javelin throwers and as a three-dimensional representation; note the clustering within international male throwers at the top, and for two females at bottom left and right (adapted from Schöllhorn and Bauer, 1998).

Figure 4 Cross correlation functions at various phase lags between the throwing arm shoulder and elbow angles for four throws by the 1996 men's Olympic gold medallist (adapted from Morriss *et al*., 1997).

Figure 5 Partitioning of variability between its various sources: a) typical operator with markers, b) typical operator without markers, c) group with markers, d) group without markers (adapted from Bartlett *et al*., 2005 under review).

Figure 6 Contour map of simulated range thrown for different combinations of release angle and release angle of attack for the maximum release speed at which that thrower could throw and for a given model of javelin; contours are lines of constant range (adapted from Best *et al*., 1995).

Figure 7 Absolute variability, expressed as standard deviation, and relative variability, expressed as coefficient of variation, in segment end-point speeds for the three successful throws and for unsuccessful throws from the free throw line.

* * *

Figure 8 Changes in movement variability as a function of shooting distance for a typical player (from Robins, 2003).

Figure 9 Hypothetical relationship between variability and the likelihood of overuse injury with a representation of the influence of other risk factors associated with overuse injury (from Wheat, 2005).

Figure 10 Average variability in coordination patterns during treadmill (dotted line with triangles) and overground (solid line with squares) running for the joint couplings of hip flexion-knee flexion (top), hip flexion-ankle dorsiflexion (middle) and knee flexion-rear foot inversion (bottom) over the four quarters of the stance phase, where phase 1, 2, 3 and 4 are 0-25%, 26-50%, 51-75% and 76-100% of stance respectively. *Significant difference between conditions ($p < 0.05$) (from Wheat, 2005).

Figure 11 Variability in coordination patterns during overground (top), treadmill (middle) and treadmill-on-demand (bottom) running for the knee flexion-rearfoot inversion joint coupling for a typical participant; FS = foot strike, TO = toe-off (from Wheat, 2005).

Figure 12 Average coordination variability during treadmill (thin solid line with triangles), treadmill-on-demand (dotted line with circles) and overground (thick solid line with squares) running for the joint couplings of hip flexion-knee flexion (top), hip flexion-ankle dorsiflexion (middle) and knee flexion-rear foot inversion (bottom) over the four quarters of the stance phase, where phase 1,2,3 and 4 are 0-25%, 26-50%, 51-75% and 76-100% of stance respectively. *Significant difference between overground and treadmill ($p < 0.05$), $^{\#}$significant difference between overground and treadmill-on-demand conditions ($p < 0.05$) (from Wheat, 2005).

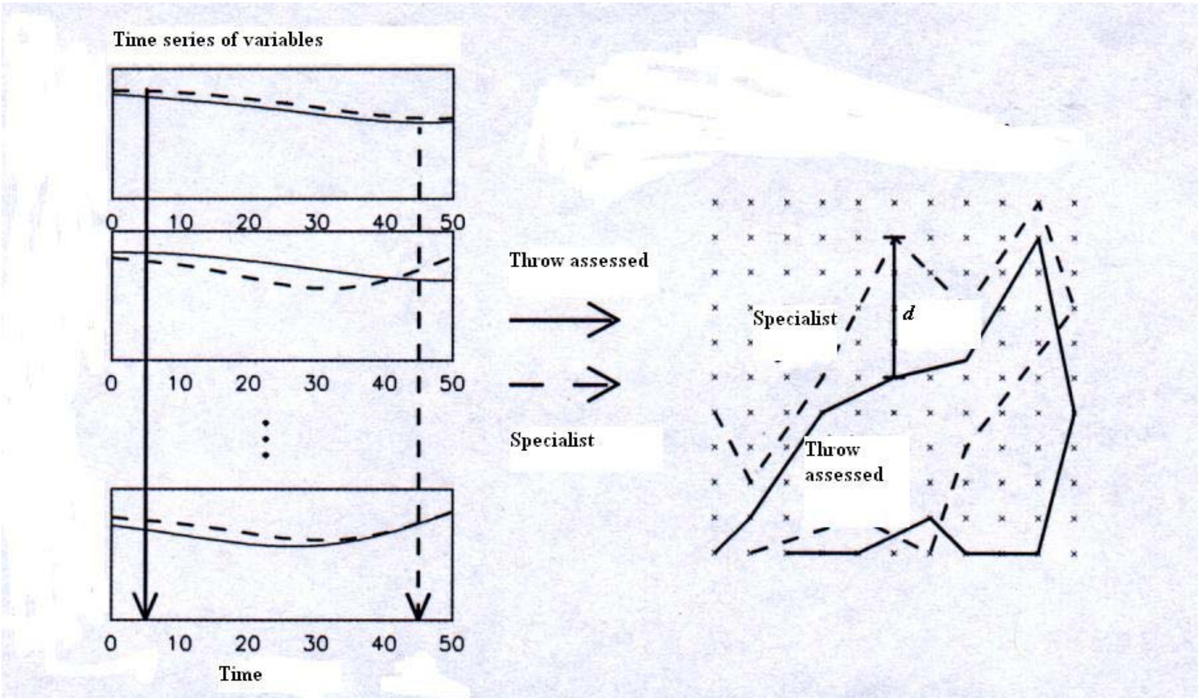


Figure 1

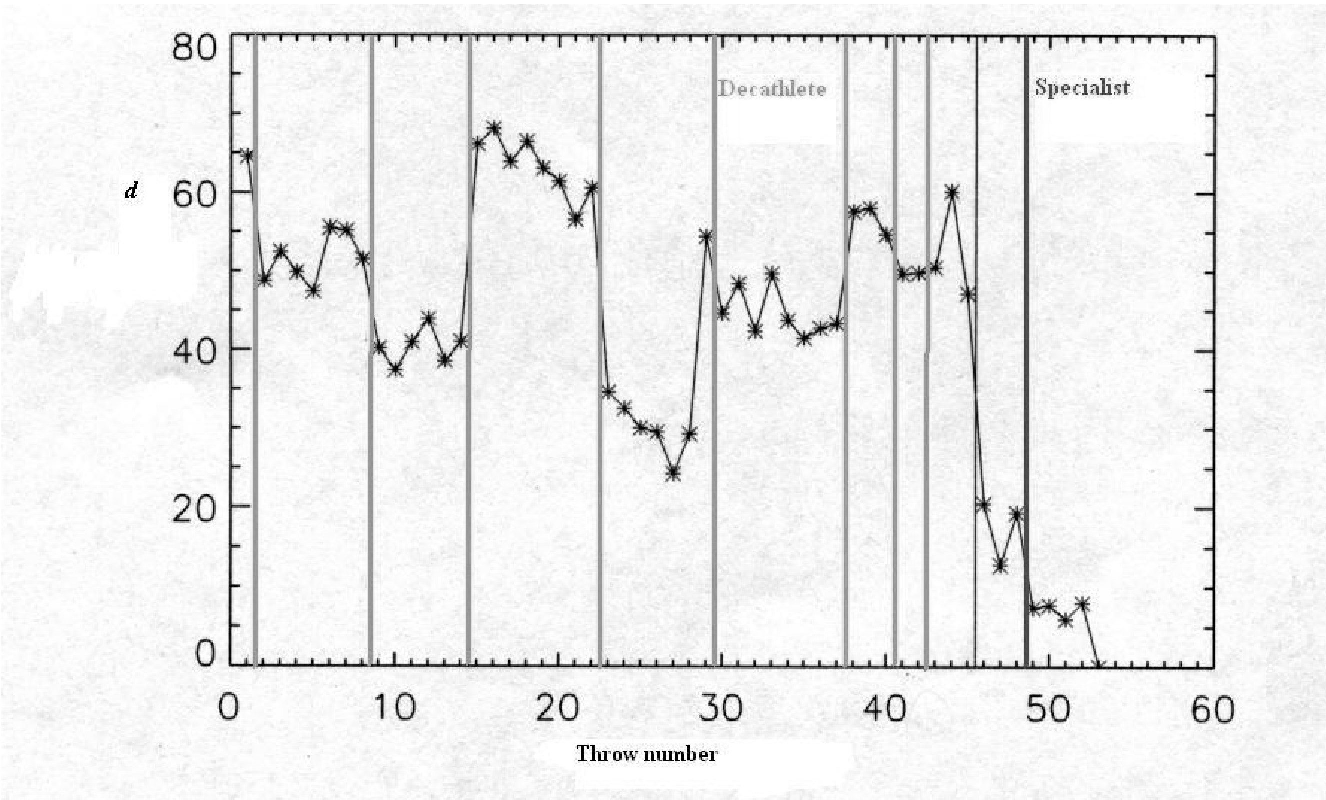


Figure 2

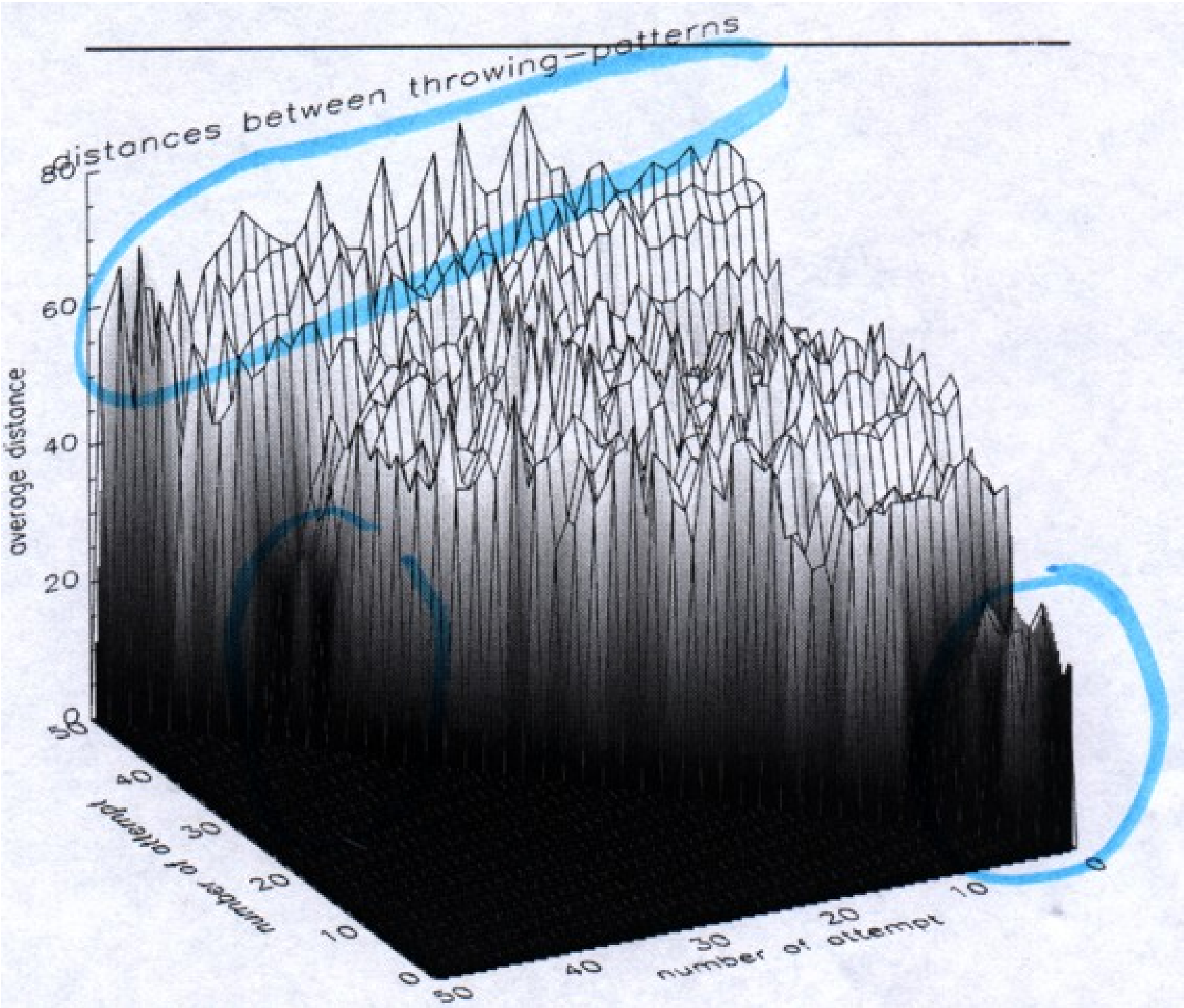

distances between throwing-patterns
average distance
80
60
40
20
0
number of attempt
50
40
30
20
10
0
number of attempt
50
40
30
20
10
0

Figure 3

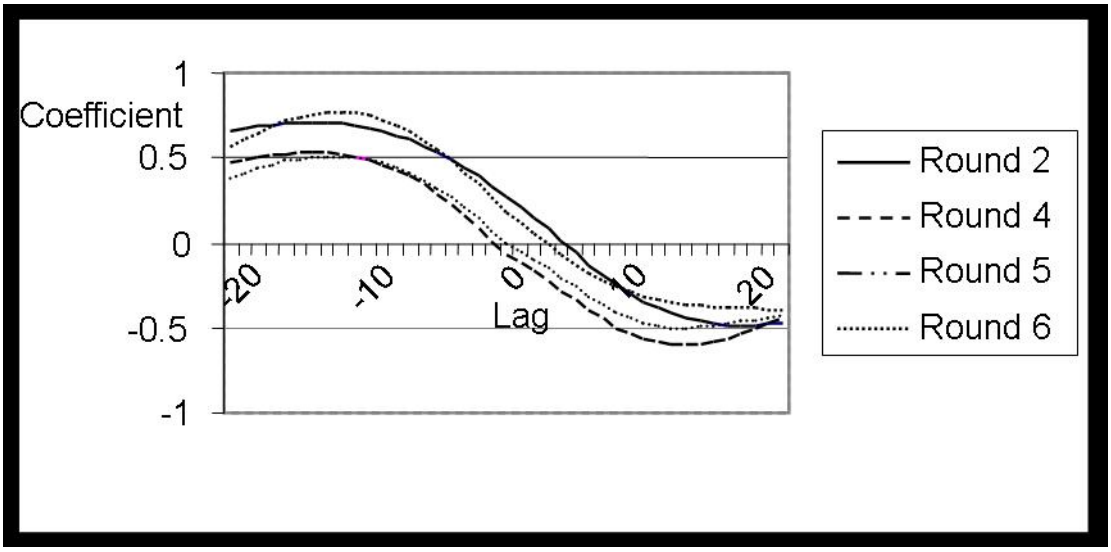
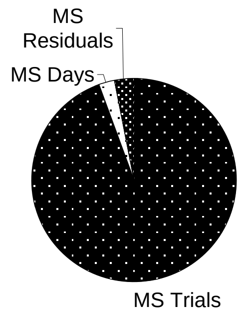
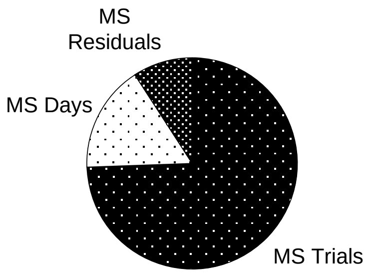
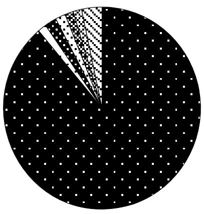


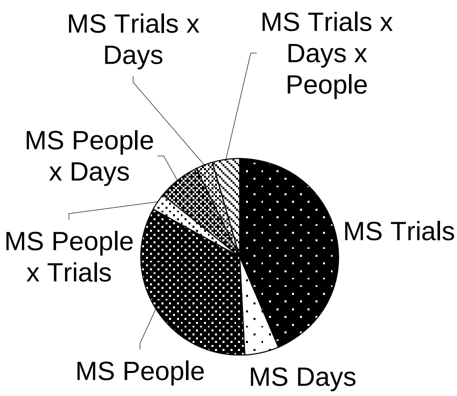
Figure 4





(a) (b)





(c) Figure 4 (d)

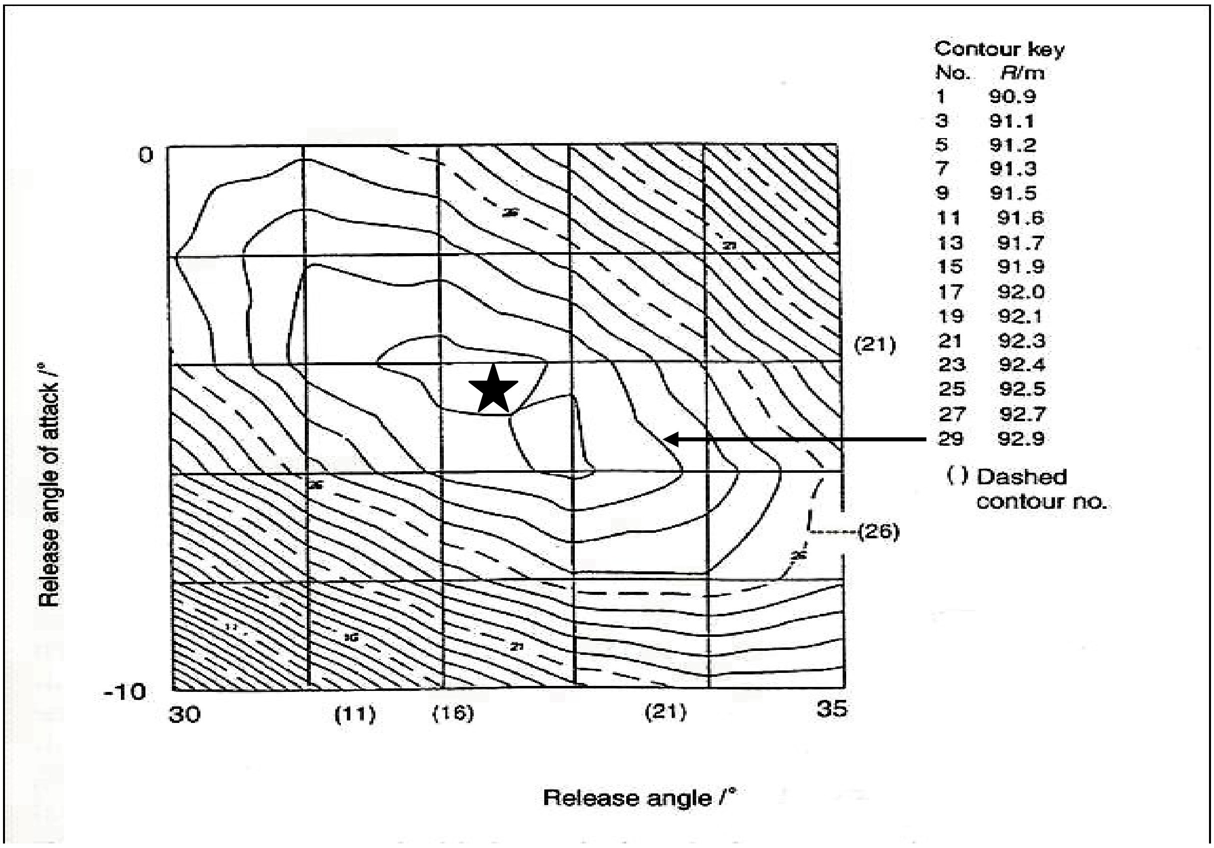

Contour key
No. R/m
1 90.9
3 91.1
5 91.2
7 91.3
9 91.5
11 91.6
13 91.7
15 91.9
17 92.0
19 92.1
21 92.3
23 92.4
25 92.5
27 92.7
29 92.9
( ) Dashed contour no.
(21)
(26)
0
-10
30
(11)
(16)
(21)
35
Release angle of attack /°
Release angle /°

Figure 6

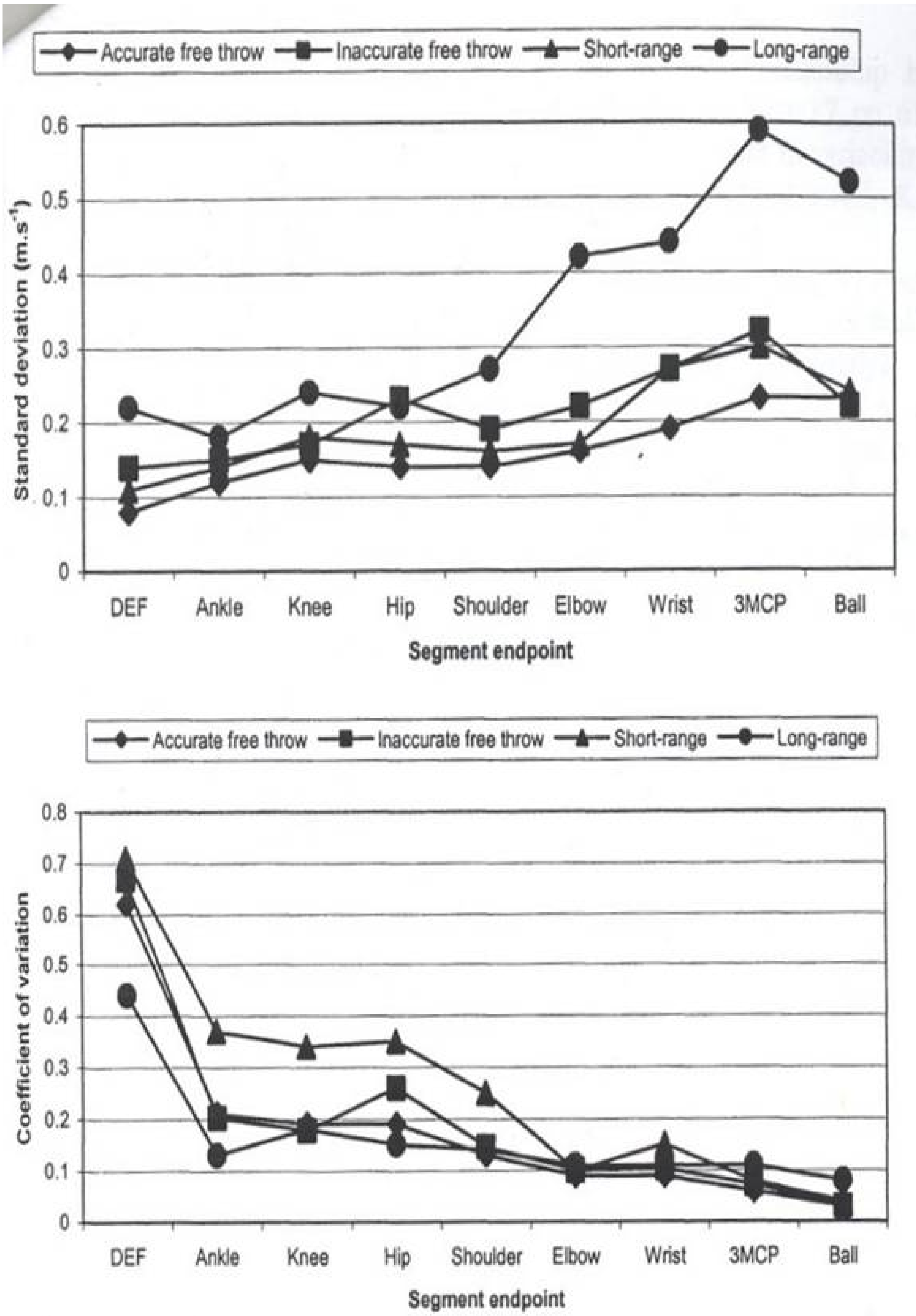

Accurate free throw
Inaccurate free throw
Short-range
Long-range
Standard deviation (m.s-1)
0.6
0.5
0.4
0.3
0.2
0.1
0
DEF
Ankle
Knee
Hip
Shoulder
Elbow
Wrist
3MCP
Ball
Segment endpoint
Accurate free throw
Inaccurate free throw
Short-range
Long-range
Coefficient of variation
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
DEF
Ankle
Knee
Hip
Shoulder
Elbow
Wrist
3MCP
Ball
Segment endpoint

Figure 7

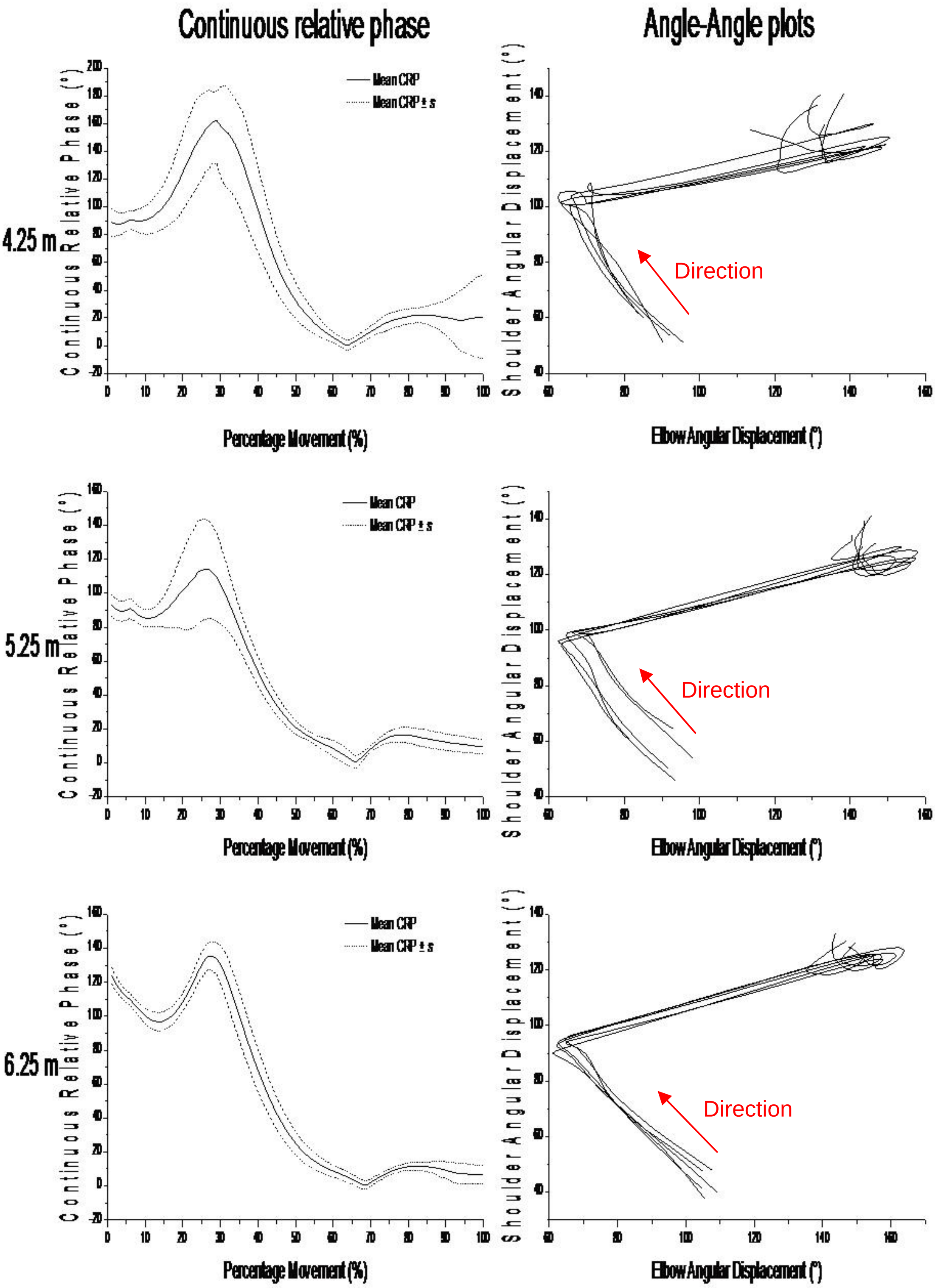

Continuous relative phase
Angle-Angle plots
4.25 m
5.25 m
6.25 m
Mean CRP
Mean CRP ± s
Continuous Relative Phase (°)
Percentage Movement (%)
Shoulder Angular Displacement (°)
Elbow Angular Displacement (°)
Direction

Figure 8

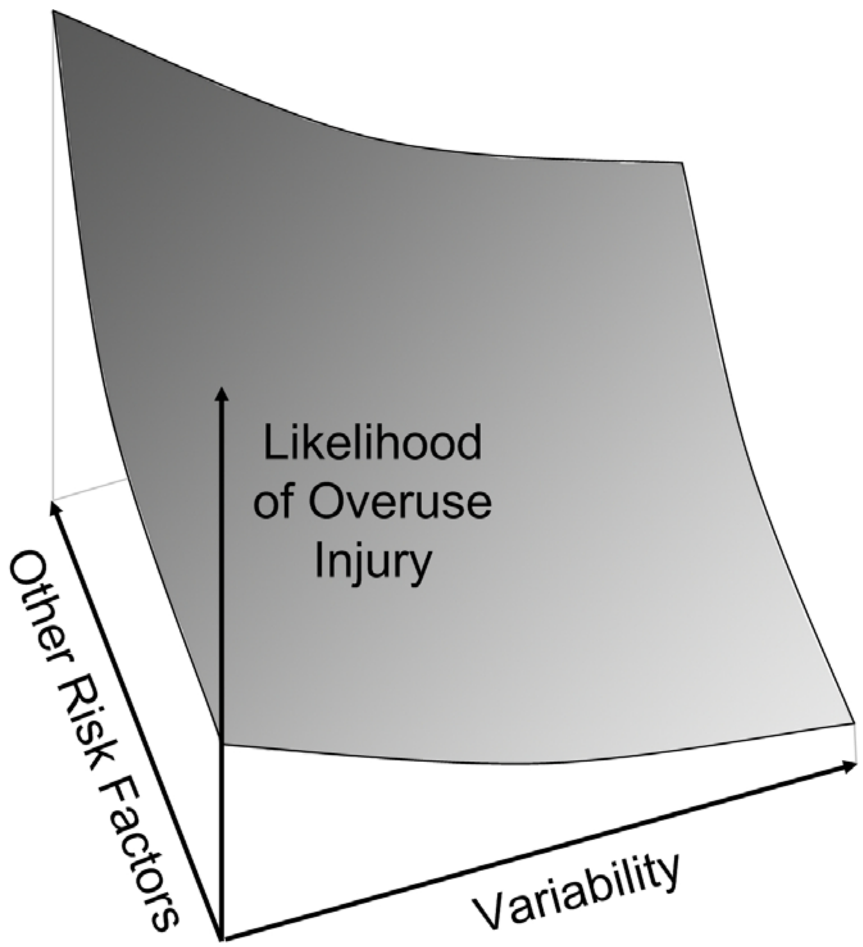

Likelihood of Overuse Injury
Other Risk Factors
Variability

Figure 9

781

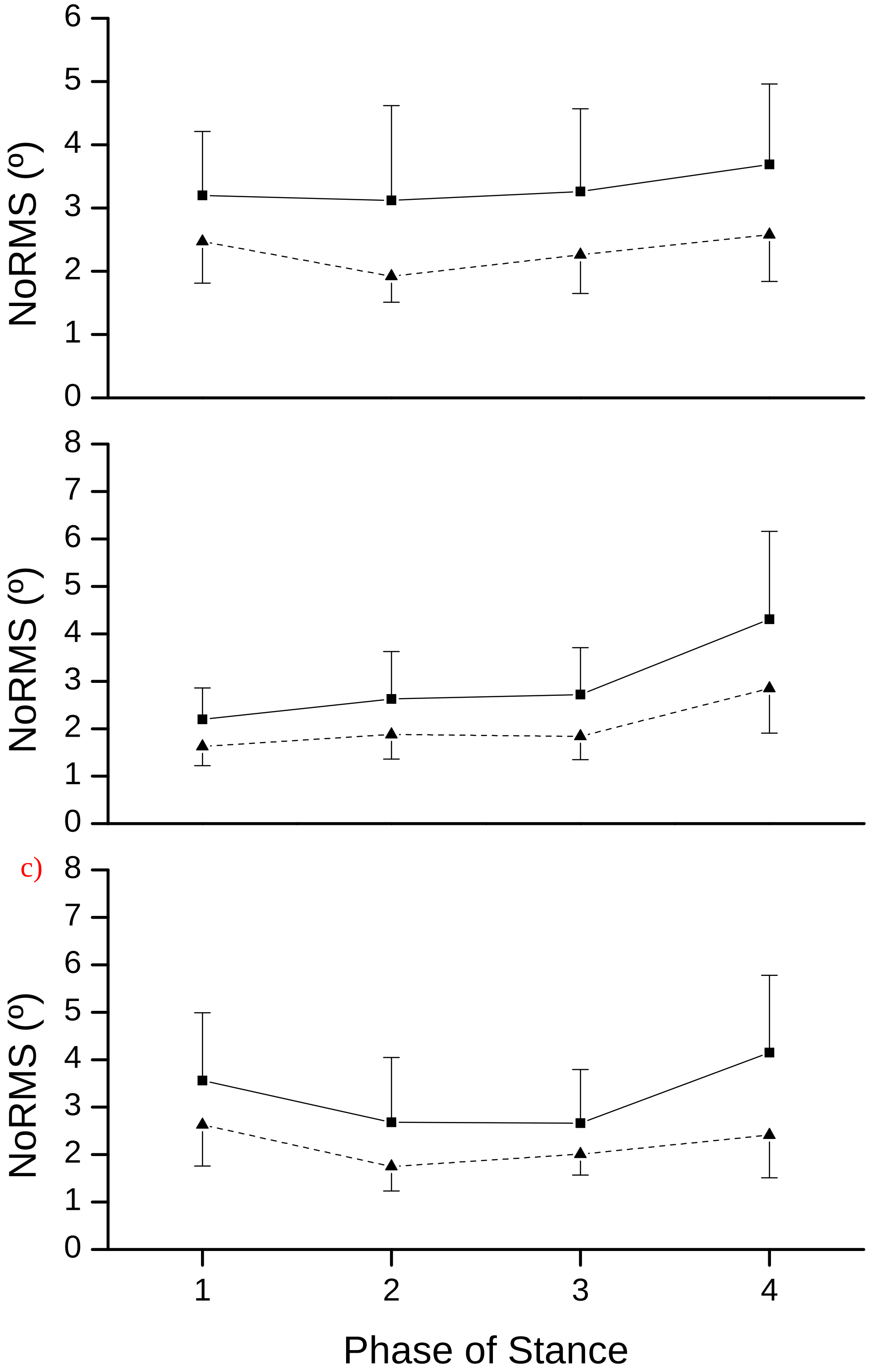


Figure 10

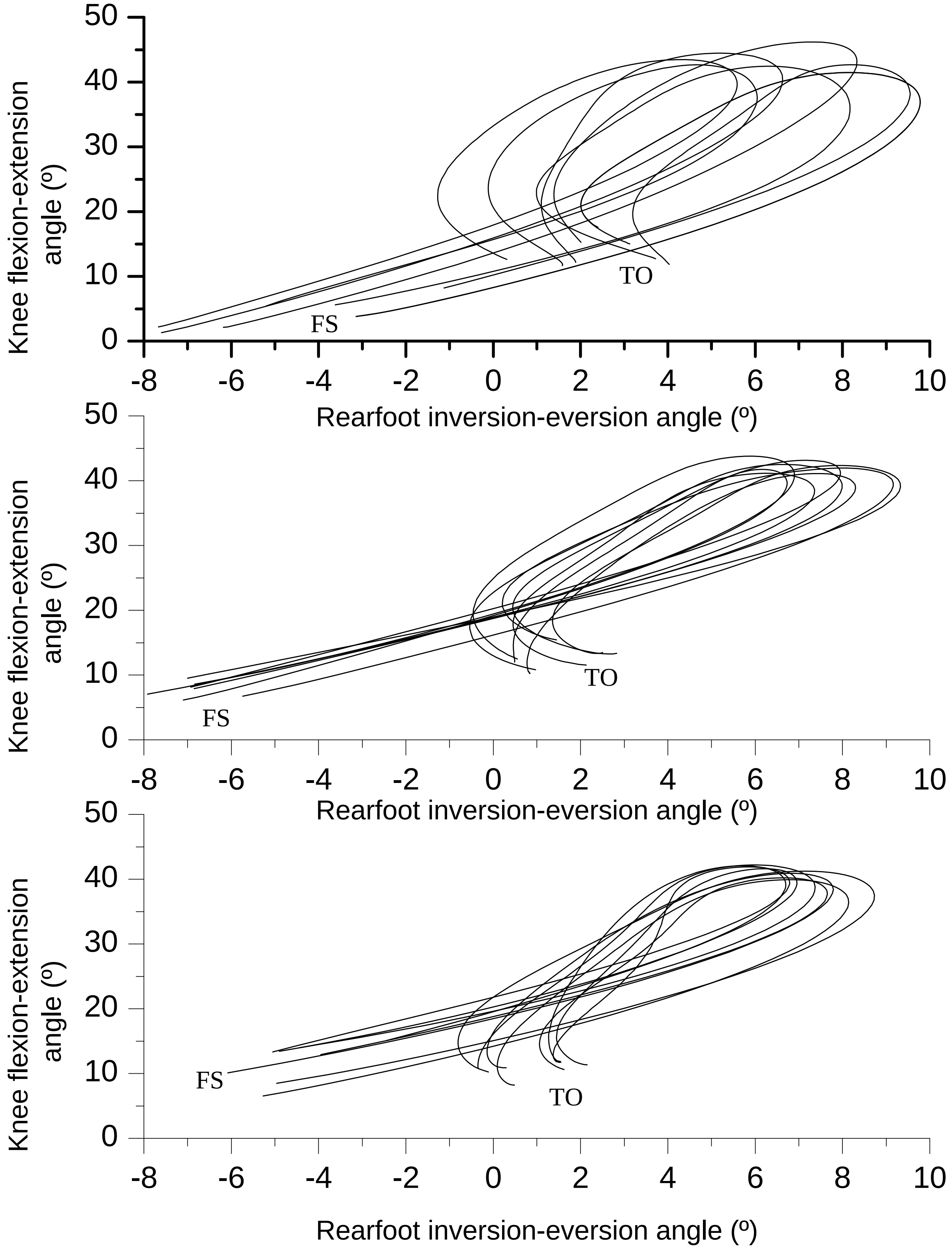
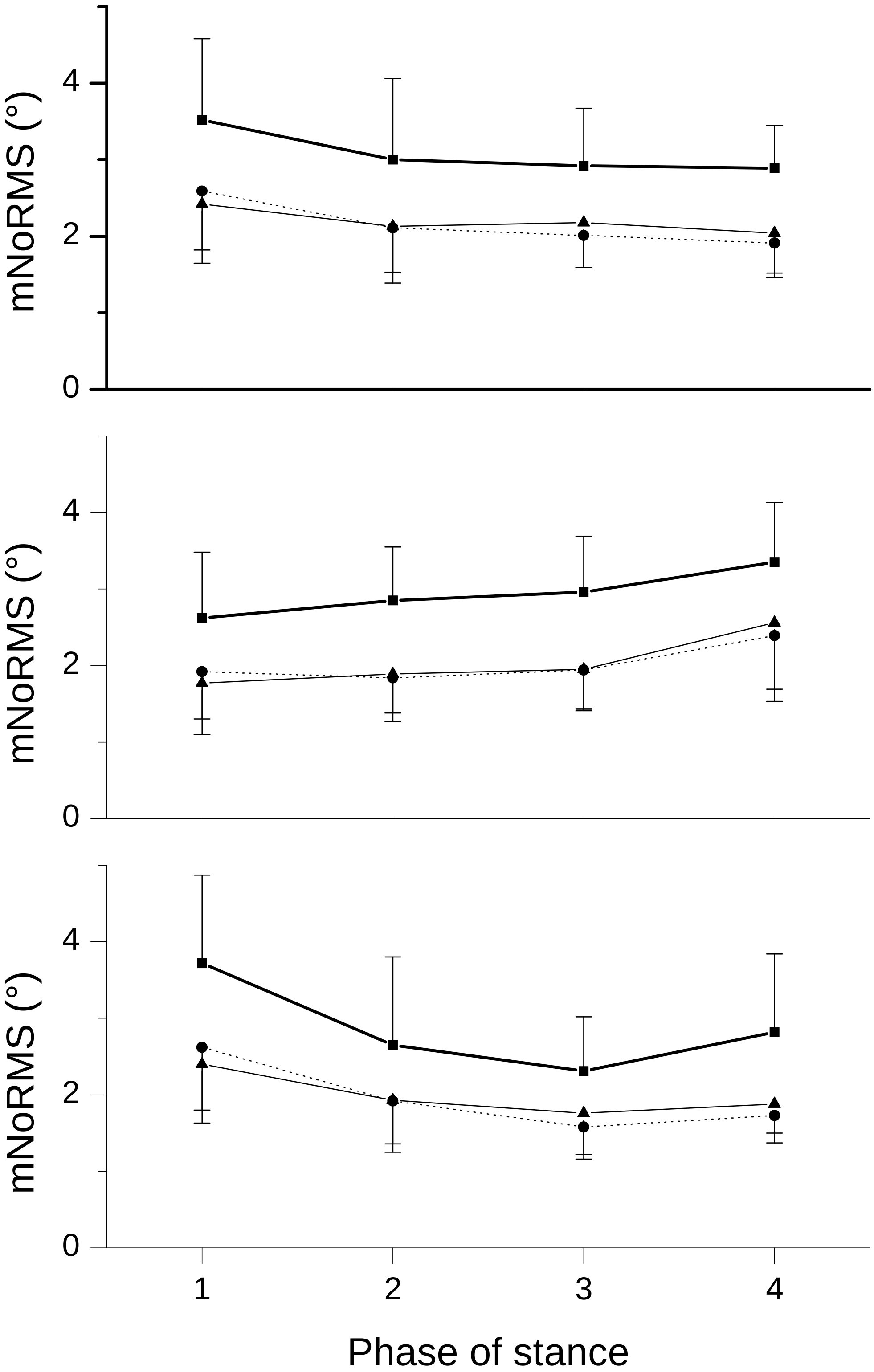

Knee flexion-extension angle (º)
Rearfoot inversion-eversion angle (º)
FS
TO
Knee flexion-extension angle (º)
Rearfoot inversion-eversion angle (º)
FS
TO
Knee flexion-extension angle (º)
Rearfoot inversion-eversion angle (º)
FS
TO

Figure 11



783

784 Figure 12