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Multidimensional joint coupling: a case study visualisation approach to movement coordination and variability

Gareth Irwin[a], David G. Kerwin[a], Genevieve Williams[b], Richard E. A. Van Emmerik[c], Karl M. Newell[d] and Joseph Hamill[c]

[a]Cardiff School of Sport, Cardiff Metropolitan University, Cardiff, UK; [b]College of Life and Environmental Sciences, University of Exeter, Exeter, UK; [c]Biomechanics Laboratory, Department of Kinesiology, University of Massachusetts, Amherst, MA, USA; [d]Department of Kinesiology, University of Georgia, Athens, GA, USA

ABSTRACT

A case study visualisation approach to examining the coordination and variability of multiple interacting segments is presented using a whole-body gymnastic skill as the task example. One elite male gymnast performed 10 trials of 10 longswings whilst three-dimensional locations of joint centres were tracked using a motion analysis system. Segment angles were used to define coupling between the arms and trunk, trunk and thighs and thighs and shanks. Rectified continuous relative phase profiles for each interacting couple for 80 longswings were produced. Graphical representations of coordination couplings are presented that include the traditional single coupling, followed by the relational dynamics of two couplings and finally three couplings simultaneously plotted. This method highlights the power of visualisation of movement dynamics and identifies properties of the global interacting segmental couplings that a more formal analysis may not reveal. Visualisation precedes and informs the appropriate qualitative and quantitative analysis of the dynamics.

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Motor behaviour; dynamical systems; coordination; visualisation; coaching

Introduction

Understanding the learning and performance of motor skills requires the analysis of not only the outcome of the action for each attempt, in addition, the organisation of the individual joint motions and their coordination. This is particularly the case for the whole body motions of sport skills that reflect the challenge of Bernstein's problem (Bernstein, 1967): namely, how the many degrees of freedom (DF) of the system are organised so as to master the redundancy of the system. Bernstein gave emphasis to the joint motion DF, but even at this macroscopic level the problem for analysis is the challenge of a multivariate system (Bernstein, 1967).

Biomechanics, with its emphasis on the measurement of the kinematics and kinetics of human movement, has investigated the motions of the individual DF in action. Coordinative structure theory (Kugler, Kelso, & Turvey, 1980) and coordination dynamics (Haken, Kelso,

CONTACT Gareth Irwin girwin@cardiffmet.ac.uk

& Bunz, 1985) have emphasised the coordination between the individual DF in movement and action. Importantly, it is the combination of measurement levels (task outcome, DF motion, DF coordination) in the context of their redundancies within and between levels of analysis that reflects what Saltzman and Kelso called task dynamics (Saltzman & Kelso, 1987).

There has been considerable progress in understanding the coordination and control of bimanual coordination tasks that is anchored in the principles of the HKB model (Haken et al., 1985; Turvey, 1990). There has been less progress in investigating Bernstein's (1967) problem in the multivariate multi-joint movement task context. This problem is reflected in the range of examples apparent in the learning and performance of whole-body actions and sport skills. It is our view that progress in the multivariate (multiple beyond 2 DF case) can only be addressed by a multivariate system (network)-oriented approach to the problem that goes beyond the bivariate bimanual case.

Movement science has become increasingly interested in the problem of coordination, control and skill. As a result, there has been an increased use of multivariate statistics, non-linear dynamics and network analyses to the problems of system decomposition. For example, the linear statistics of principal component analysis (Daffertshofer, Lamoth, Meijer, & Beek, 2004; Lamoth, Daffertshofer, Huys, & Beek, 2009), canonical analysis (Ivanovic & Ivanovic, 2011; Kakebeeke et al., 2014) and cluster analysis (Sailer, Engert, Dietrich, & Straube, 2000) have been used to decompose the multivariate relations in movement and posture tasks. Stergiou (2004) has introduced some analytic tools from non-linear methods to the analysis of human movement. There have also been non-linear network machine learning approaches to motor control through support vector machines (Chow, Davids, Button, & Rein, 2008).

The purpose of this paper is to re-emphasise the power of the visualisation of movement dynamics to explore and understand the coordination problem at the individual case study level in sports biomechanics. The visualisation of complex movement sequences is shown as a precursor to the use of formal quantification methods. We follow Abraham and Shaw (1984) who provided a unique contribution in formalising a set of strategies for the visualisation of the geometry of behaviour that was grounded in dynamics. This visualisation framework is not a replacement for the formal mathematics of dynamics but an adjunct to it that reflects the power of visual representations to understanding and describing the motion of dynamical systems. A visualisation approach to the movement coordination problem can provide a qualitative (topological) and quantitative description of movement and its constraints (McGinnis & Newell, 1982).

There are several useful consequences to the visualisation of the movement coordination and control problem. First, it requires one to select, a priori, the relevant dimensions and variables on which to represent the motion of the system. This is not necessarily a straightforward decision particularly when there are multiple DF, but it forces an explicit determination of the coordinate frame. Second, the selection of the coordinate dimensions can occur in a theory driven or looser 'warm feeling' way about the organisation of the system. This contrasts with the multivariate statistic approach that allows the formal assumptions of the technique to find the respective relations in the data-set independent of a large degree of theoretical bias. Third, the visualisation strategy can allow one 'to see' relations in the data that may not be apparent from the more formal analysis techniques with groups of individuals. There will still be limitations arising particularly when there are multiple DF, but visualisation can provide an approach to dynamical 'data snooping' that can lead to insights prior to the selection and use of formal analysis techniques.

Methods

Participants

A priori approval was gained from Cardiff Metropolitan University's Research Ethics Committee and written informed consent obtained from the participant who was a male, international level gymnast (competing at World Championship level) : age, 24 years; mass, 69 kg; and stature, 1.67 m. The participant was healthy and without injury at the time of data collection.

Data collection

Kinematic data (200 Hz) were collected using an automated 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, Leicester, UK). Two CX1 scanners provided a field of view exceeding 2.5 m around the centre of the bar. The CODA system was aligned according to the manufacturer's guidelines.

Seven active markers were placed on the lateral aspect of the participant's right side at the estimated centre of rotation for the: glenohumeral joint, mid-forearm, lateral epicondyle of the elbow, greater trochanter, femoral condyle, lateral malleolus, fifth metatarsophalageal and the centre of the underside of the bar. Whole-body mass and height were measured using laboratory weighing scales (Avery Berkel Ltd, model ED01) and a stadiometer (Holtain, Ltd.), respectively. The inertia parameters of the gymnast were customised from a database of 30 male gymnasts generated from direct measurements using Yeadon's inertia model (Yeadon, 1990). The gymnast's height and mass were combined with limb length scaling derived from the coordinate video data.

The gymnast performed 10 sets of 10 consecutive longswings on a standard competition high bar (Continental Sports, Huddersfield, UK). Sufficient rest was provided between each set so that the gymnast did not become fatigued.

Raw marker data in the horizontal and vertical directions were identified from CODA output and all subsequent analysis took place using customised code written in MathCAD 13™ (MathSoft Engineering & Education, Inc., Surrey, UK). Coordinate data were filtered using a Butterworth low-pass digital filter with cut-off frequency set to 6 Hz that was determined based on Winter's residual analysis (Winter, 1990). Segment angles were defined with respect to the right horizontal and angular velocities determined using a variation of Ridder's divided difference method (Press, Flannery, Teukolsky, & Vetterline, 1992). The angular orientation of the gymnast about the bar was described by a circle angle. A circle angle was defined by a vector from the mass centre to bar with respect to the horizontal, where a circle angle of 90° and 450° reports the CM of the gymnast above the bar (in handstand) (Figure 1).

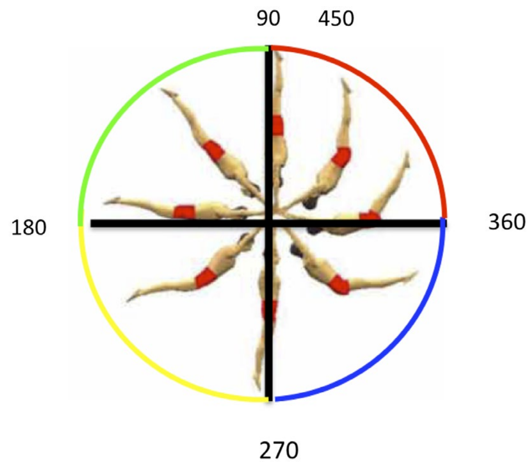

Figure 1. Angular position of the gymnast

Data analysis

Continuous relative phase (CRP) was determined using the methods of Hamill, van Emmerik, Heiderscheit, and Li (1999). CRP was calculated for pairs of segments: Arm–Trunk ‘(shoulder), Trunk–Thigh (hip) and Thigh–Shank (knee). Phase plane portraits were normalised to ±1 of the maximum rectified angle (horizontal axis) and angular velocity (vertical axis). The phase angle (φ) was calculated as the arctangent of the angular velocity over the angular displacement profile within the range $0^{o} \leq \varphi \leq 360^{o}$ and then rectified differences in phase angles of each pair of segments provided the CRP profiles according to the methods of Hamill et al. (1999). The initiating and ending swings in each set were ignored leaving the middle 8 swings from each set of 10 for analysis resulting in 80 swings for each participant (10 sets of eight consecutive swings). In order to provide intra-trial comparisons between swings, data were interpolated in 1° increments of the circle angle about the bar.

Given our interest in the coordination and variability of the highbar longswing we established a series of coordinate frames to visualise the couplings and variability of the movement sequence.

Stage one: The CRP profiles of the Arm–Trunk (shoulder), Trunk–Thigh (hip), Thigh–Shank (knee) for all 80 swings were plotted separately against circle angle. These 1-DF coordinative structures include both intra-trial and intra-participant variation. The trajectories of interacting segments represent a local state space of this skill.

Stage two: The CRP profiles of the shoulder, hip and knee were then averaged across the 80 trials to produce a mean CRP profile for each coupling. Arm–Trunk (shoulder), Trunk–Thigh (hip), Thigh–Shank (knee), respectively, were then plotted against circle angle to provide a 2 DF coordinative structure. Plotting both these 2-DF coordinative structures simultaneously against circle angle provided a more complete view of the coordinate interactions and a more global representation of the state space.

Stage three: The average CRP profiles of each individual couple were plotted simultaneously, i.e. Arm–Trunk (shoulder), Trunk–Thigh (hip), Thigh–Shank (knee) (x,y,z). In order to maintain context to the direction and magnitude, the circle angle was depicted through a colour code (green = 90–180 deg, yellow = 180–270 deg, blue = 270–360 deg,

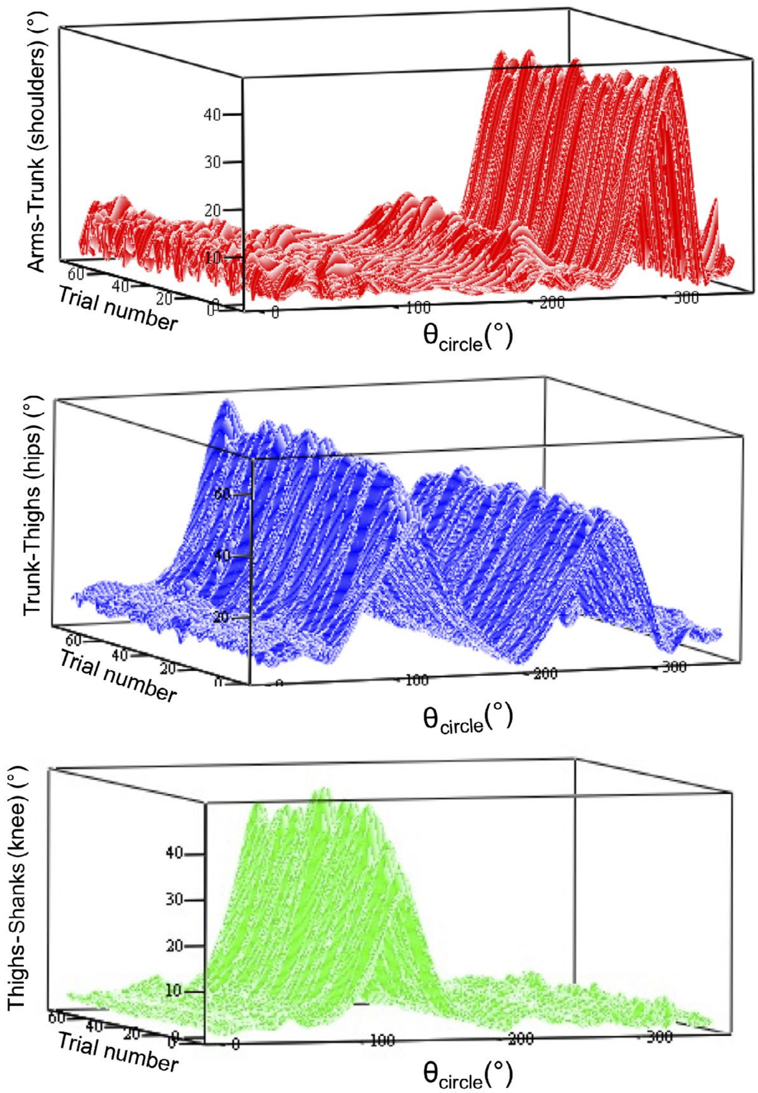

Figure 2. Continuous relative phase profiles for the Arm–Trunk, Trunk–Thigh and Thigh–Shank couplings for each looped bar longswing from 0 to 360° (*x*), for each of 80 trials (*y*) showing amplitude of CRP (*z*).

red = 360–450 deg). This representation of combined segments provides a 3-DF coordinative structure that represents a macroscopic view of the functional coordinative system. Varibility was represented as a continuous standard deviation was employed.

Results

Single couplings for each interacting segment are displayed in Figure 2. This visualisation shows the distinctive similarities in phase relationships within the individual couplings in terms of phase and magnitude. Specifically, the shoulders showed an out-of-phase peak in

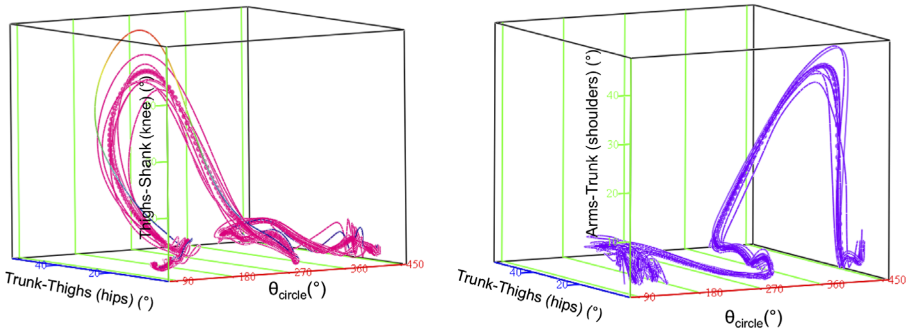

Figure 3a. LEFT: Combined continuous relative profiles for the Trunk–Thigh (hips) and Thigh–Shank (knee) RIGHT: Combined Continuous relative profiles for the Trunk–Thigh (hip) and Arm–Trunk (shoulder).

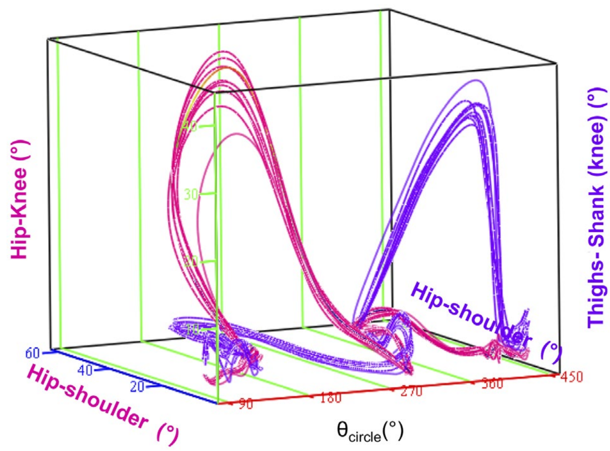

Figure 3b. Combined Continuous relative profiles for the Trunk–Thigh (hip) and Thigh–Shank (knee) with the Combined Continuous relative profiles for the Trunk–Thigh (hips) and Arm–Trunk (shoulder).

the latter stages of the circle, hips a double peak in the first and third quarters of the circle and the knee, which was most variable, showed an anti-phase peak in the first third of the skill.

The combined couplings of the hip–knee and hip–shoulder, respectively, are shown in Figure 3(a). These coupling trajectories represent a 2-DF coordinative structure and, thus, a more global profile of the interacting couplings. Combining these couplings (hip–knee and hip–shoulder) against circle angle (Figure 3(b)) provides an identification of the anti-phase locations in relation to the circle angle, specifically, the couples of the hip–knee and hip–shoulder dominating in the first and final quarter of the circle, respectively.

Simultaneously transposing the three couplings of the shoulder (arms–trunk), hip (trunk–thigh) and knee (thigh–shank) together provides a graphical representation of this interacting system (Figure 4). The visualisation of the multiple segments during this specific task provides a macroscopic coordination perspective. Figure 4 also shows this coordination structure with variability through the inclusion of the standard deviation across the 80 swings.

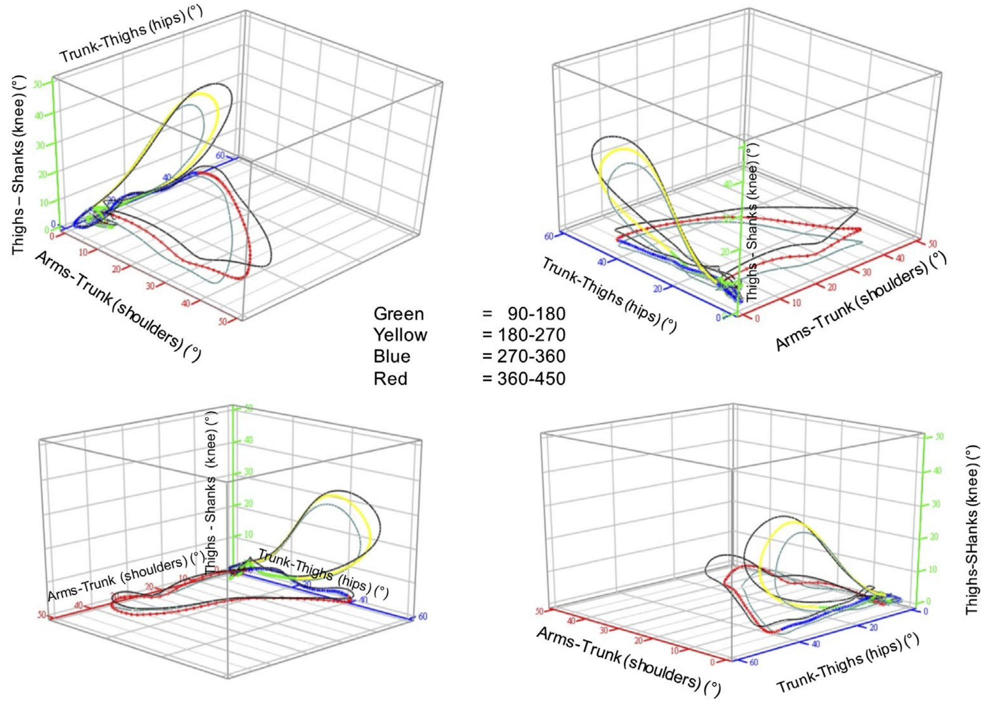

Figure 4. Continuous relative profiles and associated SD of the Trunk–Thigh (hips), Thigh–Shank (knees) and Arm–Trunk (shoulders) plotted simultaneously.
Notes: Axis: x = shoulder, z = knees, y = hips. Angular position of the gymnasts denoted via colour coding.

With the three couplings occupying the orthogonal axis, the angular position of the gymnast about the bar is described through the inclusion of colour coding (Figure 4). The angular position of the gymnast about the bar was defined by the mass centre as a vector angle projected from the centre of the bar hence providing context to this 3-DF coordinative structure. Figure 4 defines the macroscopic coordinative structure and its variability showing anti-phase couples at the hip and knee during the first (90–180 deg) and second (180–270 deg) quadrant.

It is evident from the visual depiction that the variability increases from first to the second quadrant peaking at 225 deg then, interestingly, reducing as the gymnast moves to the lower vertical. During quadrant three, the shoulder and knee couples are inversely related, as the former increases its out of phase pattern whilst the latter become more in phase. During this third quadrant the variability stays relatively stable. In the 4th quadrant (360–450 deg) the shoulder couple moves out of phase followed by the hips and knees. The variability of the coordinative structure changes as a function of the segmental interaction and the angular position of the gymnast.

Discussion and Implications

The visualisation technique presented here simultaneously transposes three CRP couplings to produce a 3D plot that provides a holistic representation of the movement coordination pattern and its variability (Figure 4). The 3D visualisation of the movement dynamics reveals specific patterns of coordination and variability employed to successfully perform this motor skill. This visual representation of movement behaviour provides an opportunity to examine the interaction of the segments of this system and its attractors (Abraham & Shaw, 1984).

The longswing on high bar is a representative task to combine knowledge of the underlying biomechanical determinants with the self-organisation (coordinative structures) of the athlete as a system (Irwin & Kerwin, 2007a, 2007b; Williams, Irwin, Kerwin and Newell, 2015a, 2015b). The visual representations provide insight into the nature and structure of this system although this is not to be confused with the somewhat predictable orbiting oscillations of the performance-based mechanics of these skills (e.g. Irwin & Kerwin, 2005). Indeed, the visual representations revealed properties of movement organisation that were masked, or not apparent, in the more standard biomechanical analyses. The coordinative structure that emerges from this 3D visualisation demonstrates that, within the action work space, there are clear phases where all three couplings merge towards a global in-phase relationship (final stages of the 2nd quadrant) before a clear hip-dominated anti-phase coordinative pattern arises (3rd quadrant). These global interactions are accompanied by a reduction in coordination variability during this key transitional phase as the performer moves through the lower part of the circle. These observations serve two purposes: (1) they highlight the overall segmental interactions and variability, i.e. the holistic nature of this skill; and (2) the importance of this key phase under the bar that is supported by the classic biomechanics of this skill.

The results of this study highlight similarities in segmental coupling within a participant across the CRP profiles (Figure 2). The knee coupling showed the highest level of variation across the 80 trials. Combining the couplings (Figures 3(a) and 3(b)) gave an indication of the changes in the coupling within the system but also the location in terms of the angular position of the gymnast on the bar. These findings concur with the functional characteristics of the skill (Irwin, Exell, Manning, & Kerwin, 2014). The assimilation of the three couplings (Figure 4) displays changes in the coordinative structure and its variability during the four quadrants of the longswing.

During the first quartile (90–180), hip coordination dominates being increasingly out-of-phase. In the second quartile (180–270), the hip and knee couplings tend to out-of-phase in line with the occurrence of the functional phase (Irwin & Kerwin, 2005). During the third quadrant (270–360), the hip is again dominant with an out-of-phase coordination pattern, with less than five degree change in the knee and shoulder couplings. In the final quartile, the shoulder couplings peaks at 40 degrees whilst the hip coupling tends to be in-phase culminating in the shoulder returning to in-phase. Throughout the 3D plot, the relatively planar trajectories of the 2nd and 4th quartile highlight that two couples tend to out-of-phase at any one time. These changes in coordination trajectories can only be observed in 3D plots of this nature, highlighting the kinematic sequencing that determines a successful performance.

Interestingly the variability of hip and shoulder is highest during the 2nd and 4th quadrants and signifies the position of a control mechanism supporting successful completion of the skill. Variability is high as the couplings tend to be out-of-phase. Maintaining the stability of the coupling and low variability in quartile 3 (270–360), as in Figure 4, links to the concept of end point variability as the gymnast performs the functional phase of the skill (Irwin & Kerwin, 2005). These three dimensional representations of the coupling variability provide a unique visualisation of the magnitude and structure of the variability in all three couplings simultaneously.

The continuous standard deviation shown in Figure 4 provides an indication of the 3D structure and nature of coordination variability. It is interesting to note that the current literature provides opposing views on the topic of inter-participant variability. For example, Wilson, Simpson, Van Emmerik, and Hamill (2008) reported high levels of coordination variability for key aspects of elite triple jump technique; whereas, Irwin and Kerwin (2007a, 2007b) found low levels of coordination variability for elite gymnasts performing longswings. More generally, coordination variability has been shown here to be a task- and a variable-specific problem. Strategies used to perform the gymnastics skill in this study may be expected to be more consistent due to their delimited nature through the constraints-to-action concept (Newell, 1986, pp. 341–360). This is highlighted throughout the literature in line with the non-linear dynamics systems approach (van Emmerik, Ducharme, Amado, & Hamill, 2016). In addition, the inclusion of the continuous nature of coordination variability across the cycle highlights discrepancies that would not be provided by focusing on specific regions.

The macroscopic approach visualised in Figure 4 builds on previous single degree of freedom approaches to coordination (i.e. Figure 2). The current approach demonstrates how adding, simultaneously, multidimensional segmental couplings and their variability across an entire movement gives an indication of the dynamic nature of the coordinative structures throughout the whole movement. It provides a visual representation of three joint couplings capturing the interaction of all degrees of freedom involved in this skill. This information may not be forthcoming in a two degree of freedom analyses. The 3D structure draws on the visualisation work of Abraham and Shaw (1984) and aligns with the theories of non-linear dynamics.

This visualisation analysis provides an adjunct to quantitative approaches rather than a replacement of them. This method provides a useful tool to describe and observe the global nature of skills and guide the priority and flow of their analysis. In addition, it highlights the need to begin to quantify the coordination of human movement between more than two segments. Finally, the individual strategies employed for these skills may provide some explanation of the differences in the amplitude and frequency of variability. The individual nature of biological systems suggests that participants meet the task demands more effectively with a unique individually characteristic organisation.

Coordinate frames other than those presented could have been selected to visualise aspects of the longswing dynamics. One candidate provides time on one dimension to observe the evolving coordination and movement variability. Any of the possible coordinate frames of reference for representing the coordination and variability of the movement could be implemented to provide information feedback to the gymnast (McGinnis & Newell, 1982).

Conclusion

In this paper, the power of visualising the coordination and variability of the movement pattern of the highbar longswing has been demonstrated. The longswing is a sports skill that has had considerable study in recent years from a biomechanical perspective and how this relates to the skill level of the gymnast (Williams et al., 2015a, 2015b, 2016). The longswing is a multivariate (multiple DF) task, but it is also rather tightly constrained by the rules of gymnastics and the physics of the body in motion. Nevertheless, it is anticipated that the visualisation approach developed here offers generality to the study of movement coordination and control in a broad range of movement skills. Furthermore, and importantly, we show that the visualisation of the relative motions of the longswing reveals properties of control that have not been forthcoming from traditional multivariate statistical analysis of biomechanics data.

Here, we were guided by our interest in visualising the coordination and variability of several joint space DF as a coordinative structure in the performance of a gymnast. The visualisation of the qualitative and quantitative properties of the movement dynamics are revealing and provide insights to guide more formal analysis of coordination and variability. The strength of our macroscopic approach is that it adds to the understanding of the complex nature of human movement as a dynamic system. The visualisation approach outlined here precedes and informs the selection of the appropriate quantitative analysis of the dynamics and hence has direct implications.

Authors' contributions

GI, GW, JH and KN drafted the manuscript; GI and GW performed literature searches and helped draft and revise the manuscript. All authors developed the methods, results and discussion. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Gareth Irwin http://orcid.org/0000-0002-3027-6775

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