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Whole-body angular momentum in a complex dance sequence: Differences across skill levels

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ABSTRACT

Due to the redundant degrees of freedom (DOF) and nonlinearity of reactional kinetic elements within the human motor apparatus, controlling the complex dynamics of the human musculoskeletal system presents considerable difficulties. Based on this challenge, Bernstein (1967) viewed skill development as the process whereby the central nervous system (CNS) gains mastery of kinematic DOF and kinetic reactional elements (passive forces, moments etc.), with the highest level of skill characterised by optimal exploitation of reactional elements in the achievement of movement goals. A previous kinematic investigation into coordination differences in a complex multidirectional dance sequence demonstrated that general unfreezing of kinematic DOF occurred as dance skill progressed (Chang et al., submitted for publication). To gain insight into the role of angular reactional elements in skill, the present kinetic study investigated angular momentum and associated variables across three skill levels (beginners, intermediates, experts) within this same complex dance sequence. The results showed that the angular momenta of segments and accompanying angular reactional elements generally increased with skill level. More specifically, the findings suggested that while improvements in movement economy from cancellation of angular momentum between body segments occur early in skill progression, later in skill progression, experts utilise increased whole-body angular momentum. Although this is energetically expensive, it may enhance the aesthetic value of dance movements, and/or have mechanical advantages. Overall, the findings here provide support for Bernstein's (1967) model of skill development. Future research should quantify the relations between energy expenditure, key biomechanical variables that reflect skill and dance aesthetics as perceived by audiences.

1. Introduction

The human musculoskeletal system consists of multiple linked segments with so many degrees of freedom (DOF) that for any given movement, many are redundant. Based on these system characteristics, Bernstein (1967) recognised two inherent motor control problems. First, due to nonlinearity of reactional kinetic elements (passive forces, moments etc.) in multilinked segments, the motor apparatus is a complex dynamic system that is highly sensitive to small state changes, and therefore control is necessarily a complex interplay between central and peripheral processes. Second, as a result of redundant DOF, there exist an infinite number of potential solutions to movement tasks (d'Avella, Saltiel, & Bizzi, 2003; Engelbrecht, 2001; Fautrelle, Ballay, & Bonnetblanc, 2010; Latash,

Turvey, & Bernstein, 1996; Prilutsky, 2000). Building on these insights, Bernstein (1967) viewed skill development as the process of the central nervous system (CNS) progressively discovering more effective solutions to these motor problems. He proposed that during the initial acquisition of a novel motor task, the kinematic DOF are frozen, thus constraining the motor system and minimising reactional effects. Then, as the task is practised, the kinematic DOF unfreeze, coupled with an increase in and integration of reactional elements, leading to improved movement economy. Bernstein (1967) viewed the highest development of skill as representing the maximal exploitation of reactional elements in the achievement of movement goals.

Bernstein (1967) skill development model has stimulated a series of studies on the changes occurring in kinematic DOF with increasing skill (Anderson & Sidaway, 1994; Broderick & Newell, 1999; Button, Macleod, Sanders, & Coleman, 2003; Chow, Davids, Button, & Koh, 2007; Ko, Challis, & Newell, 2003; Konczak, vander Velden & Jaeger, 2009; Newell & Van Emmerik, 1989; Sanders, 2007; Seifert, Leblanc, Chollet, & Delignières, 2010; Smith, McCabe, & Wilkerson, 2001; Southard & Higgins, 1987; Temprado, Della-Grasta, Farrell, & Laurent, 1997; Vereijken, Van Emmerik, Whiting, & Newell, 1992; Verrel, Pologe, Manselle, Lindenberger, & Woollacott, 2013). However, these studies have been focused largely on angular kinematics. Despite being central to Bernstein's (1967) conceptualisations, quantification of kinetics, and hence examination of the role of reactional elements in skill development, has been limited. In addition, many of the inquiries cited above have investigated simple motor tasks across a limited range of skill, which may not be generalisable to complex actions or late skill development. Finally, studies thus far have examined mainly task-specific limbs, which may not be adequate for assessing Bernstein's (1967) contentions, where a whole-body perspective appears to be necessary (Chang et al., submitted for publication). The present study is an extension of a recent whole-body investigation into coordination differences in a complex multidirectional dance sequence (Chang et al., submitted for publication), which demonstrated general unfreezing of kinematic DOF through increased motion (amplitude and speed) in most joints as skill increased. As a consequence of this greater joint motion, skill advancement is likely accompanied by an increase in the magnitude of segment angular motion and reactional elements. Accordingly, if further insights into reactional elements and skill are to be gained, then whole-body kinetics need to be investigated.

Angular momentum as a kinetic variable is a natural progression from angular kinematics, and permits the examination of angular reactional elements through the quantification of cancellations of segment to segment angular momenta. Furthermore, angular momentum has been theorised to be a task-level variable within hierarchical control (Neptune & McGowan, 2011; Ting, Chvatal, Safavynia, & Lucas McKay, 2012). Supporting this notion, whole-body angular momentum in human walking has been shown to exhibit synergistic organisation (Popovic & Englehart, 2004; Robert, Bennett, Russell, Zirker, & Abel, 2009) and is highly regulated around a minimisation strategy (Bennett, Russell, Sheth, & Abel, 2010; Herr & Popovic, 2008). This minimisation of whole-body angular momentum in walking is achieved via cancellation of segment-to-segment angular momenta, thereby reducing energetically expensive ground reaction moments (Collins, Adamczyk, & Kuo, 2009; Ortega, Fehlman, & Farley, 2008; Umberger, 2008) and contributing to overall movement economy. However, rather than this minimisation strategy holding true for all movement tasks, angular momentum may be exploited by the CNS for stability and manoeuvrability in multidirectional motor activities (Herr & Popovic, 2008; Hofmann, Popovic, & Herr, 2009; Popovic, Hofmann, & Herr, 2004). In fact, in humanoid bipedal robotics, angular momentum has been employed as a higher level control variable that can enhance centre of mass control (Hofmann et al., 2009), produce natural-looking emergent behaviour (Orin, Goswami, & Lee, 2013) and correct loss of balance, thereby allowing for locomotion on uneven surfaces (Wiedebach et al., 2016). Finally, the manipulation of angular momentum has been identified as one of three strategies humans employ to regain balance after postural perturbation (Horak & Nashner, 1986; Pijnappels, Kingma, Wezenberg, Reurink, & van Dieën, 2010; Wiedebach et al., 2016). Indeed, it is the only viable strategy when substantial perturbations occur and additional step movements are undesirable (Wiedebach et al., 2016), either because there are no feasible step locations or because the particular activity, such as netball or dance, has step constraints. For these reasons, angular momentum appears to be an important variable in the regulation of complex multidirectional skills.

Given that the goals of Latin dance are aesthetically effortless movement, rapid directional changes and constrained step patterning, it is an ideal task for examining the role of angular momentum in complex multidirectional skills. Whole-body examination of angular momentum across skill differences in Latin dance may provide further insights into the regulation of motor behaviour and the role of reactional elements in motor skill development. This may lead to increased understanding of the human motor system in general, as well as more targeted dance training and improved dance performance. Therefore, the purpose of this study was to investigate the relationship between different levels of skill (beginners, intermediates, experts) and angular momentum and associated variables in the 'Alternate Basic' in Cha-Cha-Cha, a complex, multidirectional, asymmetrical Latin dance sequence. It was hypothesised that 1) the magnitude of segment angular motion, 2) angular reactional elements and 3) movement economy would increase with skill level (hypotheses are defined in relation to specific variables within the methods).

2. Methods

The methods used in the current study have been reported in detail previously (Chang et al., submitted for publication).

2.1. Participants, task and data collection

Twenty nine dancers, aged 18–34 years, at three different levels of skill (10 beginners, 5 male and 5 female; 10 intermediates, 5 male and 5 female; 9 experts, 4 male and 5 female) volunteered to participate in this study. Selection criteria for each skill level were as follows: beginners had to be non-competitive dancers and have less than six months of dance experience; intermediates had to be 'C grade' competitive dancers with more than two years of dance experience; experts had to be 'open grade' competitive dancers with

more than seven years of dance experience. Informed consent was obtained for all participants, and all procedures were approved by the University of Sydney's Human Research Ethics Committee. Participants were required to dance 12 cycles of the Cha-Cha-Cha 'Alternate Basic' at a musical tempo of 100 bpm (≈ 4.8 s/cycle). The 'Alternate Basic' is an asymmetrical dance sequence which entails the dancer executing a 'Back Basic' with a 'Hip Twist Chasse' (instead of the 'Basic Chasse') from left to right, followed by a 'Forward Check Basic' with a 'Ronde Chasse' (instead of the 'Basic Chasse') from right to left; the sequence then repeats (for a full description, see Laird, 1998). A 14-camera infrared motion capture system (Cortex 3, Motion Analysis Corporation, Inc.) sampling at 100 Hz collected three-dimensional kinematic data, using a full body marker set comprising 59 *retro*-reflective markers.

A rigid 15-segment biomechanical model was constructed using Visual3D (Version 3.90.7, C-Motion, Inc.) to calculate the centre of mass (CoM) position of the whole-body and of each segment, and the angular momentum of local segments ($\vec{L}^i = I\omega$, where I is the moment of inertia and ω is the angular velocity). Segments were modelled as geometric shapes with the head and hands modelled as ellipsoids, and the thorax, upper-arms, forearms, pelvis, thighs, shanks and feet modelled as truncated cones. Segment mass was estimated as a proportion of the total mass of the participant (Dempster, 1955), and principal moments of inertia were modelled from the segment mass and geometry. Position data were smoothed using a fourth-order zero-lag low-pass Butterworth filter with a cut-off frequency set at 10 Hz. Variables were then exported into Matlab (version 7, The Mathworks, Inc.) for further analysis.

2.2. Biomechanical variables

Segment angular momentum for each time point of the ith segment about the whole-body CoM ($\vec{SAM}_{CoM}^i$) was determined using the following:

$$\vec{SAM}_{CoM}^i = [(\vec{r}_{CoM}^i - \vec{r}_{CoM}) \times m^i(\vec{v}^i - \vec{v}_{CoM}) + \vec{L}^i] \tag{1}$$

where $\vec{r}_{CoM}^i$ is the segment CoM position, m^i is the segment mass, $\vec{v}^i$ is the segment velocity, and $\vec{L}^i$ is the angular momentum of the ith segment about its own CoM, and $\vec{r}_{CoM}$ and $\vec{v}_{CoM}$ are, respectively, the CoM position and velocity of the whole-body. All terms are in the laboratory frame of reference. The resultant angular momentum about the whole-body CoM ($\vec{L}_{CoM}$) was then calculated at each time point as the sum of $\vec{SAM}_{CoM}^i$:

$$\vec{L}_{CoM} = \sum_{i=1}^{15} \vec{SAM}_{CoM}^i \tag{2}$$

Cancellation of segment angular momenta about the CoM ($SAMC_{CoM_j}$) occurs around the jth rotation axis (x, y, and z) when segments are rotating in opposite directions, effectively cancelling out some or all of the angular momenta of each segment. Therefore, the $\vec{L}_{CoM}$ represents the total angular momentum in the system with $SAMC_{CoM_j}$ removed.

The sum of the absolute $SAM_{CoM_j}^i$ ($\sum absSAM_{CoM_j}$) represents the whole-body angular momentum, including $SAMC_{CoM_j}$, around the jth rotation axis, and was determined at each time point using the following:

$$\sum absSAM_{CoM_j} = \sum_{i=1}^{15} |SAM_{CoM_j}^i| \tag{3}$$

Cancellation of segment angular momenta was then determined at each time point as the difference between $\sum absSAM_{CoM_j}$ and the absolute L_{CoM_j}:

$$SAMC_{CoM_j} = \sum absSAM_{CoM_j} - |L_{CoM_j}| \tag{4}$$

The percentage of segment angular momenta cancellation ($PSAMC_{CoM_j}$), around the jth rotation axis, at each time point was determined by:

$$PSAMC_{CoM_j} = \frac{SAMC_{CoM_j}}{\sum absSAM_{CoM_j}} \times 100\% \tag{5}$$

Ensemble averages of participant movement profiles across the dance cycle for each kinetic variable were established by first normalising each variable's time curve to 101 data points (Winter, 2009), representing 0 to 100% of the movement cycle, and then calculating the mean value at each percentage point over the 12 dance cycles. The variables L_{CoM_j}, $\sum absSAM_{CoM_j}$, and $SAMC_{CoM_j}$ were normalised by dividing by the product of the participant's height and mass. A list of acronyms summarises variables in Table 1.

2.3. Statistical analysis

The means across the cycle of the absolute magnitude of L_{CoM_j} ($\overline{|L_{CoM_j}|}$), $\sum absSAM_{CoM_j}$ ($\overline{|\sum absSAM_{CoM_j}|}$) and $SAMC_{CoM_j}$ ($\overline{|SAMC_{CoM_j}|}$) as well as the mean across the cycle of $PSAMC_{CoM_j}$ ($\overline{PSAMC_{CoM_j}}$), were calculated in each plane for each participant. One-way analyses of variance (ANOVAs) were conducted to examine the effects of skill level (beginners, intermediates, and experts), followed by Tukey's post hoc tests when significant results were obtained. The following were hypothesised: 1) $|\sum absSAM_{CoM_j}|$ would increase

Table 1

List of acronyms.

| Acronym	Definition
CoM	Centre of mass
$\vec{L}^i$	Angular momentum of the ith local segment
$\vec{SAM}_{CoM}^{i}$	Segment angular momentum of the ith segment about the whole-body CoM
$\vec{L}_{CoM}$	Angular momentum about the whole-body CoM
$SAMC_{CoMj}$	Cancellation of segment angular momenta about the whole-body CoM around the jth rotation axis (x, y, and z)
$\sum absSAM_{CoMj}$	The sum of the absolute segment angular momentum about the whole-body CoM around the jth rotation axis (x, y, and z)
$PSAMC_{CoMj}$	Percentage of segment angular momenta cancellation about the whole-body CoM around the jth rotation axis (x, y, and z)
$|\overline{L_{CoMj}}|$	Mean across the cycle of the absolute magnitude of angular momentum about the whole-body CoM around the jth rotation axis (x, y, and z)
$\left\|\overline{\sum absSAM_{CoMj}}\right\|$	Mean across the cycle of the sum of the absolute segment angular momentum about the whole-body CoM around the jth rotation axis (x, y, and z)
$|\overline{SAMC_{CoMj}}|$	Mean across the cycle of the absolute magnitude of cancellation of segment angular momenta about the whole-body CoM around the jth rotation axis (x, y, and z)
$\overline{PSAMC_{CoMj}}$	Mean across the cycle of percentage of segment angular momenta cancellation about the whole-body CoM around the jth rotation axis (x, y, and z)
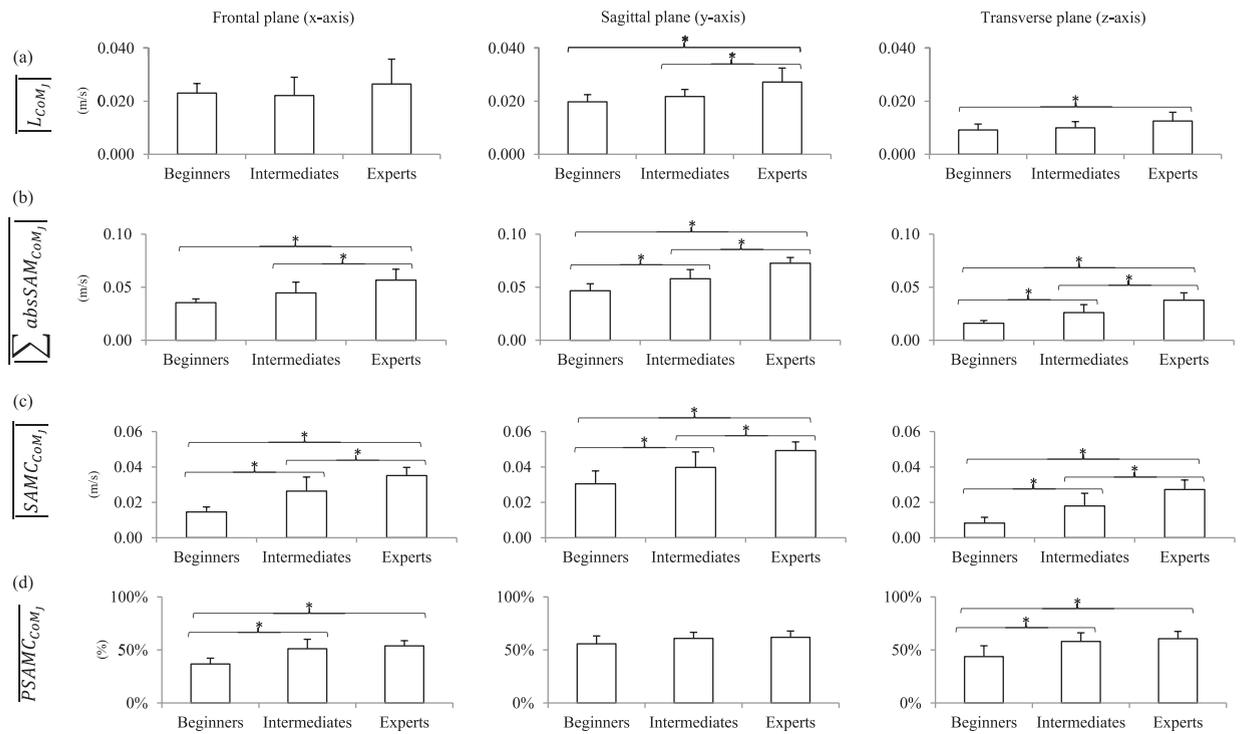
Fig. 1. Skill level groups mean $|\overline{L_{CoMj}}|$ (a), $\left|\overline{\sum absSAM_{CoMj}}\right|$ (b), $|\overline{SAMC_{CoMj}}|$ (c), $\overline{PSAMC_{CoMj}}$ (d). Error bars = one standard deviation, *$p < 0.05$. All means are normalised to body mass × height.

with skill level, indicating an increase in the magnitude of segment angular motion; 2) $|\overline{SAMC_{CoMj}}|$ would increase with skill, representing greater utilisation of reactional elements; and 3) $\overline{PSAMC_{CoMj}}$ would increase with skill level while $|\overline{L_{CoMj}}|$ would remain constant, reflecting improved movement economy.

For the ensemble averages of kinetic profiles across the dance cycle, significant group differences in each variable were determined on the basis that both groups' mean values were outside the 95% confidence intervals (CIs) of the opposing group at a given time interval. Statistical analyses were performed using SPSS (v20, IBM, Inc.).
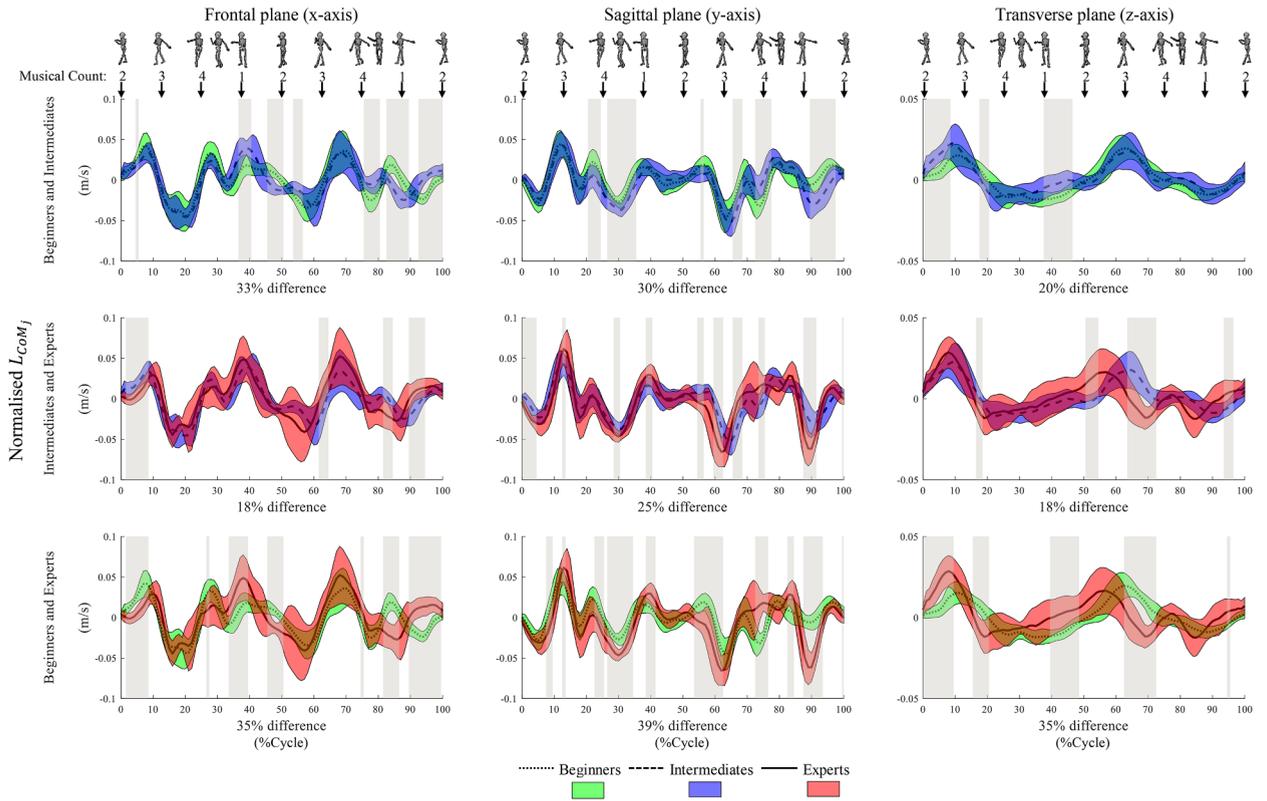
Fig. 2. Skill level group time-normalised, ensemble-averaged L_{CoMj} curves ± 95% CIs (shading). Vertical shading bars indicate group means outside the 95% CIs. % difference = proportion of cycle time that is different. Note different scaling in transverse plane (z-axis).

3. Results

3.1. Mean differences between skill level groups (ANOVA results)

Significant differences between skill levels were found in most planes of movement for the four outcome variables (Fig. 1). The $|L_{CoMj}|$ showed significant increases across skill levels in the sagittal (y-axis, $F_{2,26} = 10.18$, $p = 0.001$) and transverse (z-axis, $F_{2,26} = 4.23$, $p = 0.026$) planes, but not in the frontal plane (x-axis, $F_{2,26} = 1.00$, $p = 0.38$). The $|\sum absSAM_{CoMj}|$ showed significant increases across skill levels in all three planes of movement, frontal ($F_{2,26} = 14.56$, $p < 0.001$), sagittal ($F_{2,26} = 32.43$, $p < 0.001$) and transverse ($F_{2,26} = 30.38$, $p < 0.001$). Similarly, the $|SAMC_{CoMj}|$ showed significant increases across skill levels in the frontal ($F_{2,26} = 32.49$, $p < 0.001$), sagittal ($F_{2,26} = 16.13$, $p < 0.001$) and transverse ($F_{2,26} = 27.95$, $p < 0.001$) planes. The $PSAMC_{CoMj}$ showed significant increases across skill levels in the frontal ($F_{2,26} = 18.04$, $p < 0.001$) and transverse ($F_{2,26} = 10.97$, $p < 0.001$) planes but not in the sagittal plane ($F_{2,26} = 2.53$, $p = 0.099$).

The results of the post hoc tests on these significant effects were grouped as early (the differences between beginners and intermediates), late (the differences between intermediates and experts) and overall (the differences between beginners and experts) skill progression.

Firstly, there were no significant early skill progression differences in mean normalised $|L_{CoMj}|$ in any plane of movement (Fig. 1a). Early increases were observed in mean normalised $|\sum absSAM_{CoMj}|$ in the sagittal and transverse planes but not the frontal plane (Fig. 1b). Early increases were observed in mean normalised $|SAMC_{CoMj}|$ in all three planes (Fig. 1c). Finally, early increases were observed in mean $PSAMC_{CoMj}$ in the frontal and transverse planes but not the sagittal plane (Fig. 1d).

No significant late skill progression differences were observed in $|L_{CoMj}|$ in the frontal and transverse planes, but a late increase was observed in the sagittal plane (Fig. 1a). Late increases were observed in $|\sum absSAM_{CoMj}|$ (Fig. 1b) and $|SAMC_{CoMj}|$ (Fig. 1c) in all three planes of movement. No late differences in mean $PSAMC_{CoMj}$ were observed in any plane of movement (Fig. 1d).

Overall skill progression increases in $|L_{CoMj}|$ were observed in the sagittal and transverse planes but not the frontal plane (Fig. 1a). Overall increases were observed in $|\sum absSAM_{CoMj}|$ (Fig. 1b) and $|SAMC_{CoMj}|$ (Fig. 1c) in all three planes of movement. Overall
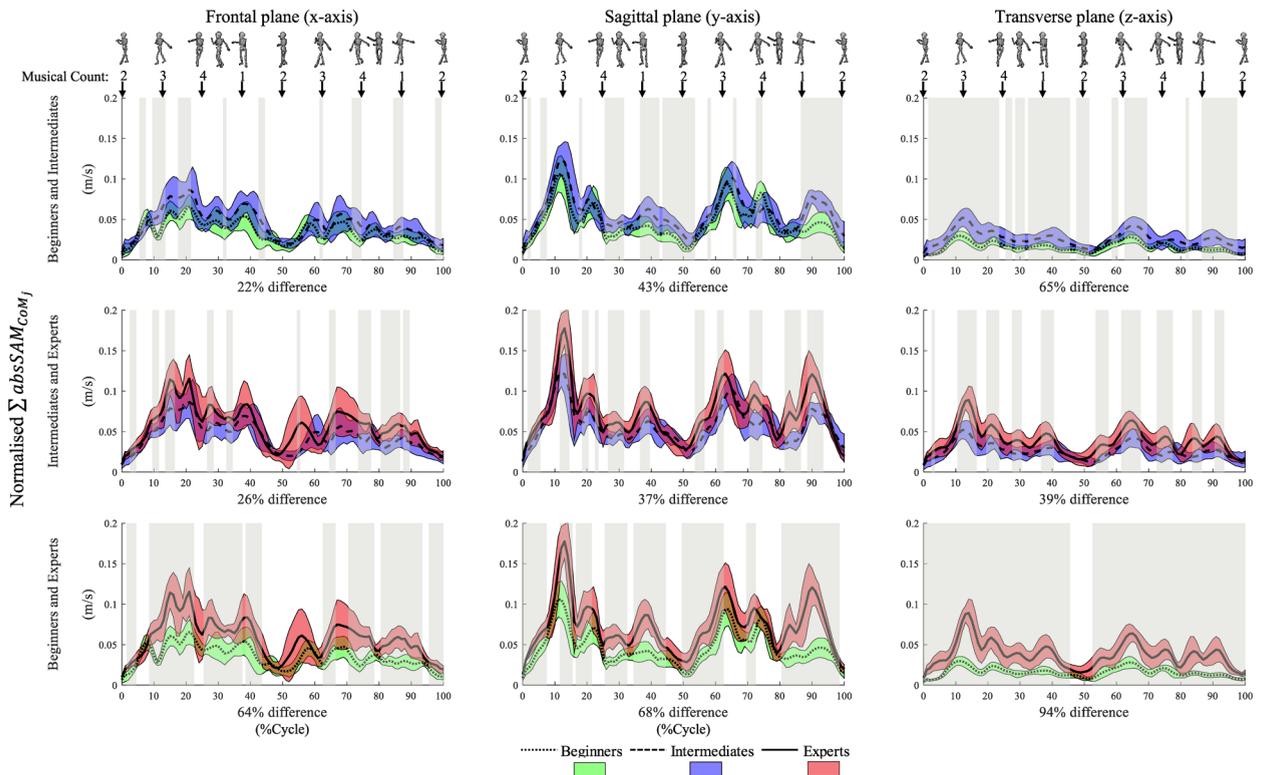
Fig. 3. Skill level groups time-normalised, ensemble-averaged $\sum absSAM_{CoMj}$ curves $\pm$ 95% CIs (shading). Vertical shading bars indicate group means outside the 95% CIs. % difference = proportion of cycle time that is different.

increases were observed in $\overline{PSAMC}_{CoMj}$ in the frontal plane and transverse planes but not in the sagittal plane (Fig. 1d).

3.2. Ensemble averages of participant movement profiles across the dance cycle

The time-normalised and ensemble-averaged curves of L_{CoMj} (Fig. 2) and $\sum absSAM_{CoMj}$ (Fig. 3) displayed similar patterns across skill groups, but with differences in amplitude of peaks and troughs and some differences in their timing between groups. The curves of $SAMC_{CoMj}$ (Fig. 4) and especially $PSAMC_{CoMj}$ (Fig. 5), however, were more clearly different in their time pattern between skill groups. Furthermore, in contrast to the ANOVA results on the means across the cycle, the results for the time-normalised and ensemble-averaged curves showed significant early, late and overall group differences across all three planes of motion for all four outcome variables, as outlined below.

Early skill progression differences were observed in the time-normalised L_{CoMj} patterns. The ensemble-averaged curves ($\pm$ 95% CIs) exhibited differences totalling 33%, 30% and 20% of the total cycle in the frontal (x-axis), sagittal (y-axis) and transverse (z-axis) planes, respectively (Fig. 2). The $\sum absSAM_{CoMj}$ curves exhibited differences totalling 22%, 43% and 65% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 3). Early differences were also exhibited in the patterns of the $SAMC_{CoMj}$ curves, revealing differences representing 64%, 44% and 68% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 4). Early skill progression differences in the patterning of $PSAMC_{CoMj}$ curves and 95% CIs exhibited differences totalling to 60%, 16% and 36% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 5).

Late skill progression differences in the patterning of time-normalised ensemble-averaged L_{CoMj} curves exhibited differences totalling to 18%, 25% and 18% of the total cycle in the frontal (x-axis), sagittal (y-axis) and transverse (z-axis) planes, respectively (Fig. 2). Late skill progression differences in the $\sum absSAM_{CoMj}$ curves represented 26%, 37% and 39% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 3), while $SAMC_{CoMj}$ exhibited differences totalling 30%, 19% and 33% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 4). Late skill progression differences in patterning of the $PSAMC_{CoMj}$ curves exhibited differences totalling to 21%, 9% and 11% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 5).

Overall skill progression differences in the patterning of time-normalised L_{CoMj} ensemble-averaged curves represented 35%, 39% and 35% of the cycle in the frontal (x-axis), sagittal (y-axis) and transverse (z-axis) planes, respectively (Fig. 2). Overall skill progression differences in the patterning of $\sum absSAM_{CoMj}$ curves totalled 64%, 68% and 94% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 3), while $SAMC_{CoMj}$ exhibited differences totalling 77%, 58% and 84% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 4). Overall skill progression differences in $PSAMC_{CoMj}$ time curves totalled to 60%, 24% and 47% of the total cycle in the frontal, sagittal and transverse planes, respectively (Fig. 5).
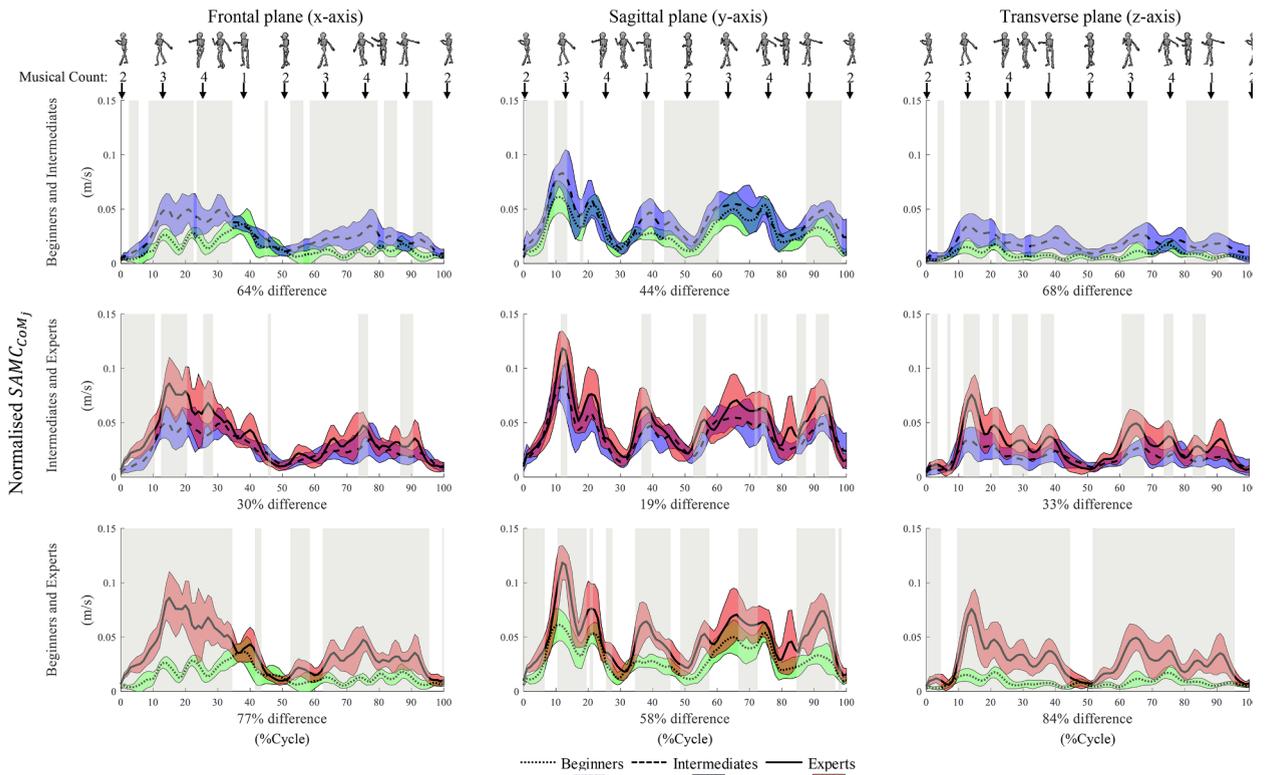
Fig. 4. Skill level groups time-normalised, ensemble-averaged $SAMC_{CoM_j}$ $\pm$ 95% CIs (shading). Vertical shading bars indicate group means outside the 95% CIs. % difference = proportion of cycle time that is different.

4. Discussion

This study examined the effects of dance skill level on angular momentum and associated variables in the 'Alternate Basic' dance sequence, and showed that the sum total of absolute segment angular momenta ($\sum absSAM_{CoM_j}$) increased in all movement planes throughout skill progression from beginners to intermediates and then to experts (Fig. 1b, Fig. 3). This result was in agreement with our first hypothesis that as dance skill develops the magnitude of segment angular motion increases. It is also in line with previous findings that increased motion (amplitude and speed) appears to be related to increased aesthetic value in dance (Chang et al., 2016; Chang et al., submitted for publication; McCarty, Hönekopp, Neave, Caplan, & Fink, 2013; Neave et al., 2010; Torrents, Castañer, Jofre, Morey, & Reverter, 2013). That is, when dancing, better dancers do more.

The increase in segment motion was accompanied throughout skill progression by an increase in cancellation of angular momentum between segments ($|SAMC_{CoM_j}|$) that occurred in all movement planes. This finding was in line with our second hypothesis and indicates greater utilisation of angular reaction elements as a function of increasing skill. Our third hypothesis posited that the percentage of segment momenta cancellation ($PSAMC_{CoM_j}$), which represents the percentage of segment angular momenta that is not energetically expensive (not requiring ground reaction moments), would increase with skill level, while whole-body angular momentum ($|L_{CoM_j}|$) would remain constant, reflecting improved movement economy. This indeed was observed early in skill progression (between beginners and intermediates), with $PSAMC_{CoM_j}$ increasing in the frontal and transverse planes and some patterning changes occurring in the sagittal plane also (Fig. 5), while $|L_{CoM_j}|$ was unchanged in any plane (Fig. 1a). Hence, improvements in movement economy from segment momentum cancellations occurred early in skill development.

The whole-body angular momentum ($|L_{CoM_j}|$) did not remain constant throughout skill progression, however, but displayed significant mean increases late in skill progression (between intermediates and experts) in the sagittal plane (Fig. 1a), and overall increases (between beginners and experts) were observed in the sagittal and transverse planes, while $PSAMC_{CoM_j}$ was unchanged late in skill progression (Fig. 1d). Taken together, the $PSAMC_{CoM_j}$ and $|L_{CoM_j}|$ findings indicate that experts had increased energy expenditure that was not accompanied by improvements to movement economy from cancellations of momentum between segments. Achieving movement that is perceived as aesthetically effortless is a common goal in dance (Cohen, 1997) and it has been suggested that energy minimisation may be a driver of coordination changes (Sparrow, Lay, & O'Dwyer, 2007; Sparrow & Newell, 1998). Consequently, we had assumed that increased movement economy from both segment momenta cancellations and whole-body angular momentum minimisation would continue to occur throughout skill development. Since the data indicate that this was not the case, the question remains; what benefit does the expert dancer gain from utilising greater whole-body angular momentum that is
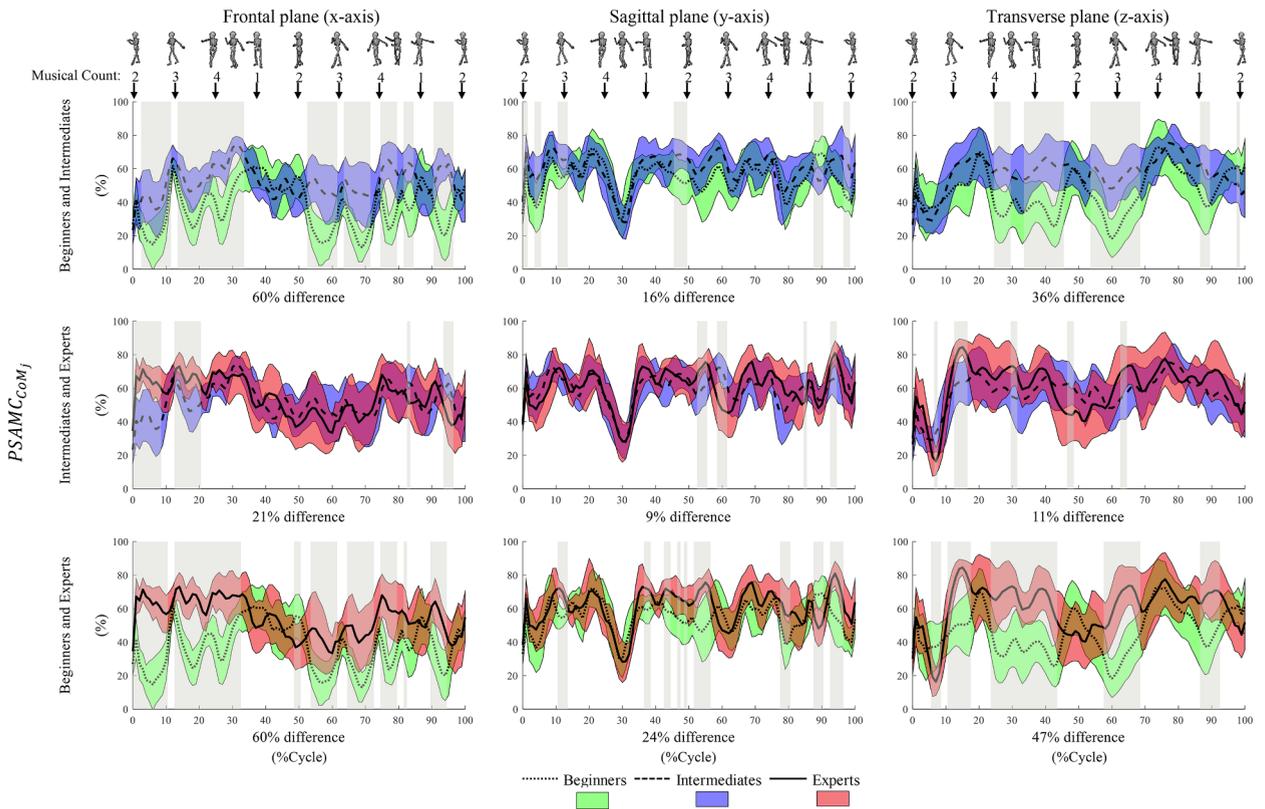
Fig. 5. Skill level groups time-normalised, ensemble-averaged $PSAMC_{CoM_j}$ $\pm$ 95% CIs (shading). Vertical shading bars indicate group means outside the 95% CIs. % difference = proportion of time cycle that is different.

energetically expensive?

One answer to this question is that expert dancers may be able to maximise aesthetic value by incorporating additional dimensions of motion. As already noted, better dancers do more, through increased whole-body angular momentum, even at the potential cost of increased energy expenditure. Hence, although the dancer may strive for economy, it does not mean that they will not increase their work output. Greater energy efficiency in any skill gives the expert performer two options: 1) reduce energy expenditure for the same amount of work (energy saved can be used later if necessary) or 2) accomplish more work for the same amount of energy expenditure. For example, a study of sheep shearers by Poole and Ross (1983) showed that while the energy expenditure of experts did not differ significantly from that of intermediate shearers, their oxygen consumption per sheep shorn was significantly lower, so that they could shear more sheep in a given time interval (thereby earning greater income). This demonstrated that the expert shearers were more efficient than their intermediate counterparts but used this greater efficiency to do more work rather than save energy. In the same way, the expert dancers here may be more efficient in the sense that they may maximise dimensions of motion, and subsequently the perceived aesthetic value, per given unit of energy expended.

An alternative to this explanation could be that greater utilisation of whole-body angular momentum, in the sagittal plane, signifies more complex movement dynamics. It has been suggested that humans enhance CoM control by altering whole-body angular momentum, improving manoeuvrability and balance (Herr & Popovic, 2008; Hofmann et al., 2009; Popovic et al., 2004). This has been supported by modelling that varied whole-body angular momentum to augment CoM force, which produced trajectories that were comparable to those of human movements (Hofmann et al., 2009). Although multiplanar, the 'Alternate Basic' dance sequence is predominantly a sagittal plane movement task (Chang et al., submitted for publication), and therefore it is conceivable that increased whole-body angular momentum in the sagittal plane in experts reflects enhanced CoM control. Nevertheless, these two accounts remain speculative and further research is needed to quantify the following: 1) the relations between energy expenditure, key biomechanical variables of skill and perceived aesthetics by audiences, and 2) the relations between whole-body angular momentum and CoM control.

Overall, the results of this study, together with findings on dance kinematics previously reported (Chang et al., submitted for publication), suggest that skill progression in the 'Alternate Basic' dance sequence can be characterised by general unfreezing of kinematic DOF that is coupled with increased utilisation of angular reactional elements. More specifically, early skill progression can be characterised by unfreezing of kinematic DOF, reorganisation of movement patterns into fewer coordinative structures (Chang et al., submitted for publication) and increased movement economy through the integration of segment to segment momentum cancellations. Late skill progression can be characterised by further unfreezing of upper limb kinematic DOF and integration of

movement towards a single coordinative structure (Chang et al., submitted for publication), accompanied by increased whole-body angular momentum that likely serves to increase aesthetic value and may also have mechanical advantages.

5. Conclusion

Angular momenta of segments and accompanying angular reactional elements both increased as a function of greater dance skill. The profiles across the movement cycle of the cancellation of angular momentum between segments and the percentage of segment angular momenta that is not energetically expensive varied between dance skill groups in all planes of motion throughout the progression of skill. The results suggested that improvements to movement economy due to cancellation of momentum between segments occur early in skill progression and that later in skill progression, although energetically expensive, dance experts utilise increased whole-body angular momentum which may increase aesthetic value and/or have mechanical advantages. Future research should quantify the relations between energy expenditure, key biomechanical variables that reflect skill and dance aesthetics as perceived by audiences, and examine the relations between whole-body angular momentum and CoM control. Overall, the findings are consistent with Bernstein's (1967) skill development model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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