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Quantifying bi-variate coordination variability during longitudinal motor learning of a complex skill

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ABSTRACT

Biofeedback (BFb) can enhance the motor learning process by guiding skill exploration. Too much BFb, however, can foster dependency leading to skill retention deficits once removed. A reducing BFb schedule could negate dependency effects, however limited methodologies exist to assess the effectiveness of an intervention during application. This research proposes a new bi-variate method ($CI2_{Area}$) to quantify coordination variability ($Coord_{Var}$) as a measure of skill exploration during a motor learning intervention. Thirty-two participants were introduced to a novel explosive-lunge task. A BFb group ($n = 16$) were provided with visual BFb on rear hip, knee and ankle joint extension magnitudes and timing during a 26-week reducing schedule BFb intervention. $Coord_{Var}$ of hip-knee and knee-ankle angular velocities were quantified by calculating the area encompassed by the 95% confidence intervals of joint coupling angular-velocity bi-variate plots ($CI2_{Area}$). Linear regressions were fitted to group and individual $Coord_{Var}$ longitudinal data. The BFb was effective in successfully altering whole limb technique within just two sessions, and these changes were retained. The BFb group demonstrated a continual increase of $Coord_{Var}$ throughout the intervention, showing continual skill exploration strategies, while the Control group remained unchanged. Gradually increasing time between sessions, using a longitudinally reducing BFb schedule, successfully negates dependency effects on BFb while also encouraging motor learning. Manipulating time between sessions allows for the provision of a high frequency of 100% BFb without fostering dependency. The $CI2_{Area}$ method was able to detect individual exploration strategies and could be used in the future to direct individual intervention modifications.

1. Introduction

Biofeedback (BFb) is an effective tool to facilitate and accelerate the skill development process (Swinnen et al., 1997; Baudry et al., 2006; Thow et al., 2012; Baggaleley et al., 2017). The provision of information relating to movement parameters, termed knowledge of performance or KP, has proven to be effective in developing specific movement patterns (Ford et al., 2015). In contrast, the constrained action hypothesis considers that feedback directed on specific movement restricts explorative strategies, and instead focus should be directed to information sources outside of the body (Wulf and Shea, 2002). Much of the constrained action hypothesis research is based on a focus of attention using instruction (i.e. how to achieve a movement pattern) rather than feedback (i.e. how a skill was executed). In comparing the focus of attention, feedback has been shown to be more effective than both internal and external instruction in targeting specific movement patterns (Keller et al., 2014). Short term BFb interventions applied to improve sporting performance (Broker et al., 1993; Eriksson et al., 2011), reduce injury risk (Crowell et al., 2010; Ford et al., 2015; Creaby and Smith, 2016) and in clinical rehabilitation (van den Heuvel et al., 2016) have shown changes to occur within just a few visits, but there is limited information on how influential or permanent these changes are. Longer, higher frequency BFb schedules, such as eight sessions during a four-week period (Mullineaux et al., 2012) and 36 sessions in 12 weeks (Viitasalo et al., 2001) have shown more permanent modifications.

Long and high frequency interventions are, however, time and resource intensive. From a theoretical perspective, the guidance hypothesis considers that while BFb is beneficial to direct motor learning, too much BFb can lead to dependency and prevent autonomous exploration processes (Salmoni et al., 1984; Sadowski et al.,

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2013). This dependency may encourage learners to bypass other important sources of feedback information needed to develop intrinsic error detection and correction mechanisms (Park et al., 2000). To reduce any dependency, BFb frequency over time can be reduced (e.g. Richards et al., 2018b) and time between visits can be increased. BFb dependency is typically evidenced with a drop-off in retention once BFb is removed (Maslovat et al., 2009), and is considered to be skill specific (Sigrist et al., 2013; Wulf and Shea, 2002). No methods have currently been used, however, to assess skill exploration during the intervention period, and such a method may be beneficial in identifying dependency or identifying occurrences of skill exploration.

Movement variability, comprising of functional and non-functional components (Cazzola et al., 2016; Hamill et al., 1999; Preatoni et al., 2013), can provide a measure of skill exploration. From a dynamical systems perspective, coordination variability ($Coord_{Var}$) is functional to allow the motor system to adapt to perturbations within the task, individual or environment (Bernstein, 1967) to facilitate consistent skill outcome (Mullineaux and Uhl, 2010; Robins et al., 2006). Consistency of skill outcome, or performance variability ($Perf_{Var}$), in contrast is often considered non-functional in influencing skill execution. An integral component of motor learning paradigms is the notion of freezing and freeing degrees of freedom with skill development during stages of motor learning within and between individuals (e.g. Berstein, 1967; Newell, 1985). $Coord_{Var}$, as an analytical tool, has been used to identify subtle differences in skill execution between novice, skilled and elite performance (Cazzola et al., 2016), and has been more sensitive when conventional biomechanical approaches have failed to distinguish between patients with subtle pathologies (Hamill et al., 1999). $Coord_{Var}$ may therefore provide a specific tool to assess skill exploration during an intervention, thus also allowing individual analyses in line with some biomechanical paradigms to assess the individual instead of the group (Glazier and Mehdizadeh, 2018; Needham et al., 2018).

Methods to quantify $Coord_{Var}$ require careful consideration. Vector coding (VC) is a widely used measure of coordination between two joints or segments (e.g. Hamill et al., 1999; Needham, 2014; 2015). The standard deviation of the vector angle (Heiderscheit et al., 2002) or standard deviation of both the vector angle and length (Tepavac and Field-Fote, 2002) provide a measure of $Coord_{Var}$, but both VC methods are susceptible to noise artefacts related to changes in vector length that can overinflate the variability output (Stock et al., 2018). An alternative bi-variate data analysis method, CI2, allows for the real-world coordination of any two time series data sets to be compared (Mullineaux, 2017). The first stage of this approach applies ellipses to encompass multiple trials of the bivariate data at each time point, with the ellipse axes scaled to 95% confidence intervals (95%CI). Stock et al. (2018) used these 95%CI ellipses to encase multiple trial angle-angle vector end points, identifying the area of these ellipses to be more robust to the statistical artefacts found using VC. CI2 uses quadrilaterals to connect consecutive ellipses to create 95%CI boundaries for the entire time series. The CI2 Matlab code provided by Mullineaux (2017) can be modified to extract the area of these quadrilaterals ($CI2_{Area}$) to provide a measure to statistically compare the spread, or $Coord_{Var}$, between any bi-variate time series.

Therefore, the aims of this research were to: (1) identify when changes occurred in targeted BFb variables during a 6-month longitudinal BFb intervention of a complex skill, and; (2) apply a new measure of coordination variability, $CI2_{Area,}$ to assess skill exploration as a measure of BFb effectiveness or dependency during the intervention.

2. Methods

2.1. Participants

Following institutional ethical approval, thirty-two healthy participants were recruited who were physically active, injury free, aged 18–40 years old and provided informed consent. Individuals were also screened for green-red colour blindness. Participants were randomly assigned into either BFb ($n = 16$; 7 male, 9 female; means ± SD; age 26 ± 5 years, height 1.71 ± 0.06 m, mass 67.4 ± 10.76 kg, leg length 0.91 ± 0.04 m) or Control groups ($n = 16$; 8 male, 8 female; age 24 ± 4 years, height 1.72 ± 0.10 m, mass 70.1 ± 14.9 kg, leg length 0.92 ± 0.06 m).

2.2. Procedure

Participants visited the laboratory on six occasions over a six-month period structured as a longitudinally reducing schedule, meaning an increase in duration between each visit (i.e. from 24 h increasing up to 12 weeks between visits). During the first week participants attended three sessions, spaced 24–48 h apart. During visit one, all participants undertook three blocks (6 lunges/block) of 'self-learning' following instruction on a novel lunge touch task to propel themselves forward as quickly as possible and use a 20 cm long pointer to strike a 15 × 15 cm target placed 1.5 leg lengths away from the front foot (Fig. 1). Each foot was on an individual force plate, with the front foot pointed toward the target and the rear foot perpendicular to the target. Elbows were tucked in, with participants crouching to 130° of flexion at the rear knee.

The task was based on the explosive element of an attacking lunge in fencing. A measure of task success was maximal horizontal centre of mass (CoM) propulsion as linked to lunge success in fencing (Yiou and Do, 2000; Bottoms et al., 2013). Following the self-learning, the BFb group were provided with instruction on BFb. Within 10 s of each lunge each BFb participant received BFb on the magnitude and timing of rear leg hip, knee and ankle maximal angular extension velocities. The BFb was displayed as a bar-chart with a colour coding system used to demonstrate sequencing information using joint angular velocity timing (green-signifying proximo-distal sequencing; red identifying joints that were out of sequence; Fig. 2). Participants were instructed to obtain proximo-distal sequencing, which has been linked with successful fencing attacking lunge performance (Mulloy et al., 2018), while also trying to beat their personal best maximal joint angular velocities that was displayed as an overlaid red dotted line for each joint. The personal best trial was the trial with the greatest ankle plantar-flexion maximal velocity during that session.

All subsequent sessions comprised of one block of retention lunges (no BFb) followed by three blocks of BFb throughout the intervention. Following the intervention week, participants returned at 4–6 weeks (blocks 15–18) and 13 weeks (blocks 19–22), and then for a final retention session at 26 weeks (block 23; Fig. 3). The Control group matched all lunges but received no BFb throughout.

2.3. Data analysis

Kinematic data were collected using 12 Raptor cameras sampling at 150 Hz with Cortex v5.3 software (Motion Analysis Corporation, Santa Rosa, CA). Kinetic data were sampled at 1500 Hz through two piezoelectric force plates (9281E, Kistler, Switzerland). Thirty 12.5 mm retro reflective markers were placed on lateral anatomical landmarks of the whole body, with four additional markers placed on the target, and three on the hand-held pointer.

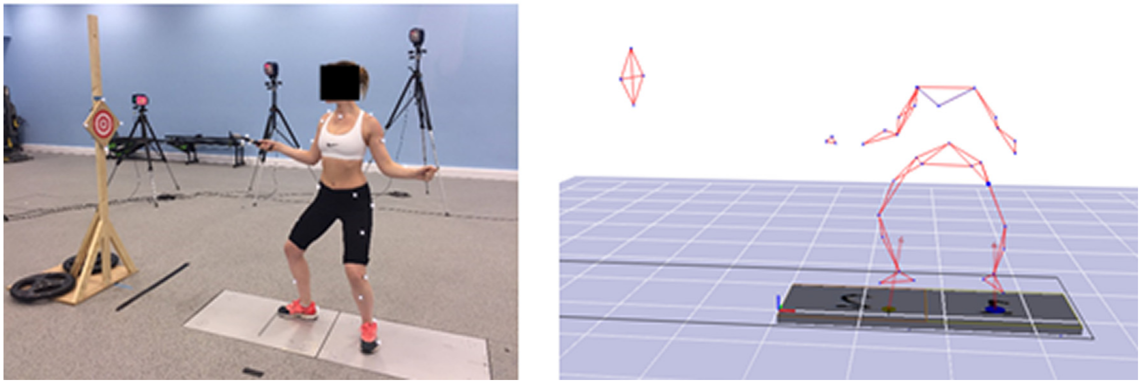

Fig. 1. Photograph (left) and motion capture software screenshot (right) of a participant in the start pose, and illustrating the marker set up, target and force plate position.

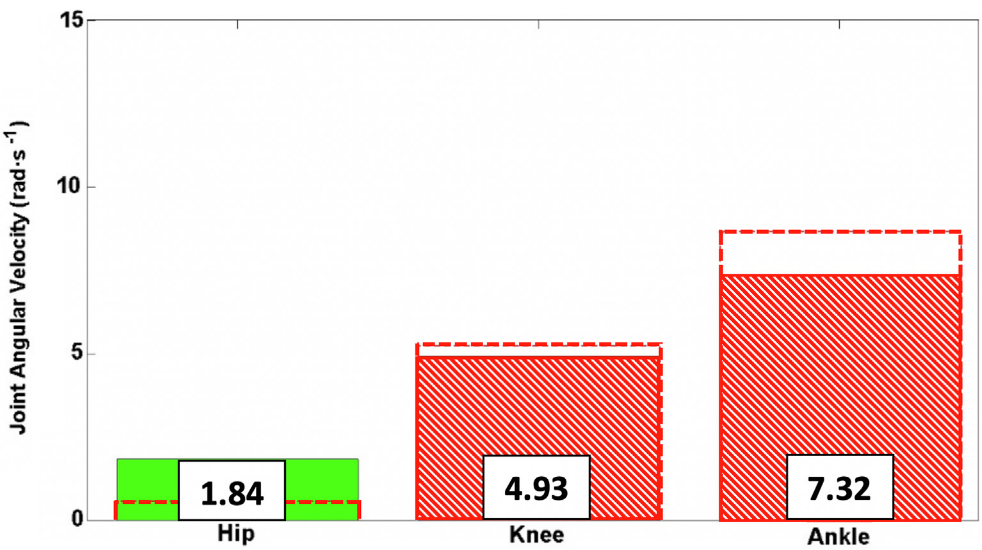

Fig. 2. Biofeedback presentation on the magnitude and timing of rear leg hip, knee and ankle maximal angular extension velocity. The red-dotted line represents the session personal best trial for all three joints. Colour coding was used to display joint sequencing information, with patterns added here for visual clarity. All green (no pattern) signified proximal to distal sequencing, and red (striped pattern) identifying joints that were out of sequence (knee and ankle in this example). Values indicate joint angular velocity for the last trial completed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Schematic representation of longitudinal data collection protocol. Each square represents 1 block. SL = self-learning, where no BFb was provided; BFb = 100% BFb (or no BFb for Controls) and R = a retention block. The order of blocks are referred to in the text from 1 to 23. Blocks are separated by 2–3 min within a session, and sessions are on different days.

Custom written Matlab code (R2015a, Mathworks, Natick, MA) was used to analyse each trial. All data were smoothed using a zero lag, fourth-order, Butterworth low-pass filter with cut off frequencies of 10 Hz for kinematic and 50 Hz for kinetic data. Kinetic data from the rear foot force plate were used to identify key events to extract BFb data for presentation. Two key events were defined; onset of force (F_O) and take off (F_{TO}). F_O was identified as the first frame that the rear leg resultant force was exceeded and remained greater than 10% body weight from the combined front and rear leg force plates. A robust F_{TO} time event was identified as the point that the differentiated rear leg resultant force data crossed zero following peak force. Push off ($F_{PushOff}$) was the phase defined from F_O to F_{TO}. Throughout $F_{PushOff}$ three-dimensional (3D) vector angles were calculated for the rear leg hip, knee and ankle using thigh, shank and ankle segments. The thigh segment was defined between the greater trochanter (GT) to the lateral femoral condyle markers, the shank segment from the lateral femoral condyle to the lateral malleolus markers, and the foot segment from the lateral malleolus to the fifth metatarsal markers. The hip joint angle was defined as the angle between the thigh segment relative to the forward horizontal, the knee joint angle between the thigh to the shank segments, and the ankle joint angle between the shank to the foot segments. Local maxima joint extension velocities were identified for the three rear leg joints and were presented as a percentage change relative to the final block of 'self-learning' lunges (i.e. block 3 = 0%).

2.4. Coordination variability calculation

Hip, knee, and ankle joint velocity time series data were used to assess $Coord_{Var}$. Angular velocities were selected for analysis as the primary variable targeted by the BFb. Due to two missing blocks of data, one BFb participant was removed from the $Coord_{Var}$ analysis. Hip-knee and knee-angle joint couplings $Coord_{Var}$ were quantified using a modification of a bivariate analysis method (CI2, Mullineaux, 2017) to extract the CI2 area ($CI2_{Area}$). The first three stages of CI2 were from code provided by Mullineaux (2017) to: (1) calculate 95%CI ellipses around the cluster of joint coupling angular velocity data points for each frame; (2) join the centres of consecutive ellipses to define the direction vector, and; (3) create convex quadrilaterals to provide 95%CI borders along the entire time series (described in more detail in Fig. 4). $CI2_{Area}$ extracts the area encompassed by these quadrilaterals throughout $Push_{Off}$ calculated using the Matlab function 'polyarea'. A larger $CI2_{Area}$ was considered to demonstrate a greater exploration of the joint angular velocity coupling. $CI2_{Area}$ provided a discrete value for each block, for each participant, for the entire 26-week intervention as a measure of $Coord_{Var}$.

2.5. Statistical analysis

2.5.1. Kinematic changes

Piecewise linear regressions were used to determine the session in which a change in learning, or session breakpoint (S_{BP}), occurred for the local maxima joint extension velocities. This process allowed for an identification of where improvements in skill plateaued during the BFb schedule over the 26 weeks. Single outliers were removed using a median anomaly detection method (Mullineaux and Irwin, 2017). Following confirmation of a normal distribution (Shapiro-Wilk test > 0.05), an independent *t*-test was used to confirm that the BFb had improved targeted kinematic variables more than the Control group at the S_{BP} for hip, knee and ankle peak angular velocity percentage changes. Peak angular velocity changes at retention time points for each joint were analysed using mixed ANOVAs (2 group × 3 times of $Retention_{Wk4-6}$, $Retention_{Wk13}$ $Retention_{Wk26}$). Where 95%CI were greater than zero

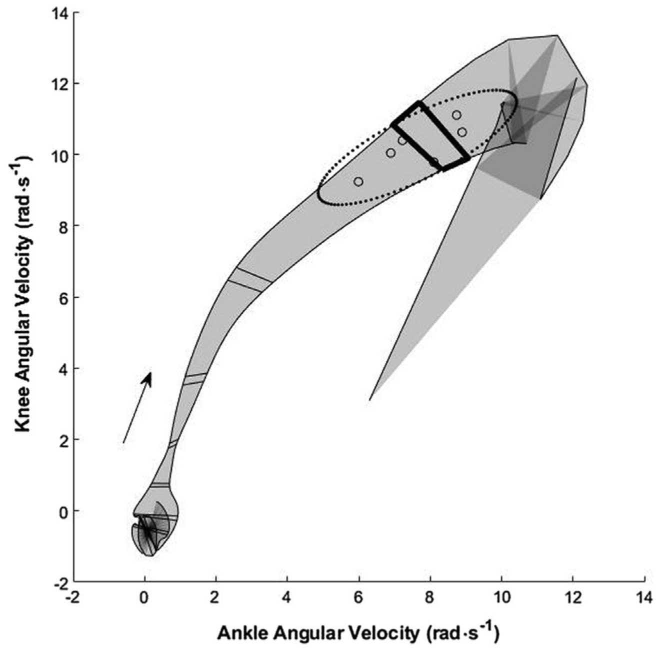

Fig. 4. Example of $CI2_{Area}$ applied to the knee-ankle angular velocity joint coupling. The quadrilaterals at every 10% time points are illustrated for 6 trials, with the ellipse and raw data (data points) at 80% included for visual purposes. The 95% confidence ellipses encompass the data points at each time point throughout the data series, with the ellipse centres joined to create the direction vector. The points of the ellipse border perpendicular to the direction vector for two consecutive ellipses are then used to create quadrilaterals for the whole time series, with the area of the quadrilaterals being summed to provide $CI2_{Area}$.

would be considered to indicate learning had occurred, and in combination with no significant interactions would indicate that learning was relatively permanent. Descriptive statistics were presented as means ± 95%CI, and alpha was set at 0.05.

2.5.2. Changes in coordination variability

To determine changes in $Coord_{Var}$ across the 26 weeks, simple linear regressions were fitted to the $CI2_{Area}$ means for both groups and both joint couplings. The $Coord_{Var}$ gradients ($CV_{Gradient}$) and 95%CI of the gradients ($95\%CI_{Gradient}$) of these regressions were calculated, and where the BFb group's $CV_{Gradient}$ was greater than the Control group's $95\%CI_{Gradient}$ indicated that the BFb group had improved significantly more than the Control group. This process was repeated on an individual level for each participant in the BFb group to assess if their individual responses were significantly better than the Control group. This group and individual process for $Coord_{Var}$ was repeated for Performance variability ($Perf_{Var}$) using $Perf_{Var}$ gradients ($PV_{Gradient}$), where $Perf_{Var}$ was quantified as the coefficient of variation (standard deviation divided by the mean × 100) of the peak horizontal CoM velocity (calculated as horizontal impulse divided by mass, with initial CoM velocity at F_O of 0 m·s^{-1}).

3. Results

3.1. Changes in kinematics

The session of the breakpoint (S_{BP}) was identified to occur within the second visit for all three joints in the BFb group (block 9, 8 and 8 for hip, knee and ankle joints respectively; Fig. 5) and not to occur at all for the Control group. At S_{BP} the BFb group kinematics (mean ± 95%CI: hip 42 ± 23%; knee 29 ± 12%; ankle 31 ± 24%) were also significantly greater than for the Control group

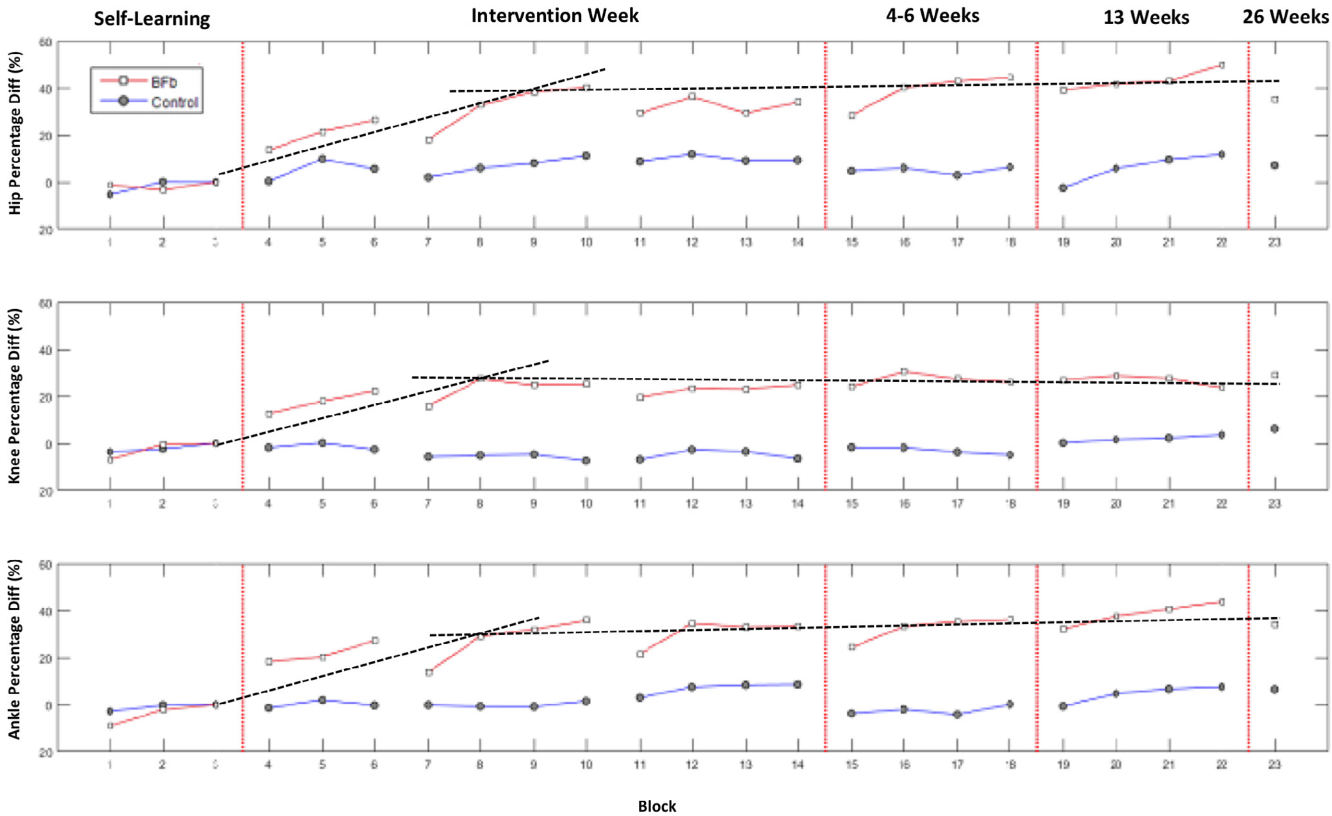

Fig. 5. Mean percentage change of joint angular velocities for biofeedback (BFb) and Control groups (0% at block 3). Each shape represents one block. The red vertical dashed lines separate sessions (Self learning, Intervention, 4–6 Weeks, 13 Weeks and 26 Weeks). Black dashed lines represent simple piecewise linear regressions, and the breakpoint (S_{BP}) in the regression lines indicate where learning changes from increasing to plateauing occurring in session 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(hip 8 ± 10%, $p = 0.007$; knee −5 ± 9%, $p < 0.001$; ankle −1 ± 12%, $p = 0.014$). Following S_{BP}, at the retention visits, the BFb participants retained significantly greater peak extension angular velocities (Table 1; $p < 0.05$). Further, for all three joints and all three retention visits the 95%CI for the BFb were greater than the pre-intervention of 0% indicating that the BFb group were able to retain the kinematic changes induced by the BFb conditions throughout the 26 weeks. In contrast, the Control group 95%CI all encompassed 0% indicating that no learning had occurred.

3.2. Changes in coordination variability

The BFb group showed a continual increase in $CI2_{Area}$ over time in both the hip-knee ($CV_{Gradient}$; BFb = 0.7 versus Control = −0.9), and knee-ankle $Coord_{Var}$ ($CV_{Gradient}$; BFb = 3.14 versus Control = −0.24) versus decreases in the Control group (Fig. 6). The increase in variability in the BFb group did not plateau over time. Group $Perf_{Var}$, as a measure of task performance variability, was unchanged over the 6-months in both groups ($PV_{Gradient}$; BFb = −0.01 versus Control = 0.00).

On an individual level, for hip-knee $Coord_{Var}$ 7 out of 15 BFb participants and for knee-ankle $Coord_{Var}$ 8 BFb participants showed significantly greater increases throughout the reduced schedule biofeedback intervention relative to the Control group (Table 2). In contrast, $Perf_{Var}$ did not alter over time for most participants, with only two of the BFb group's $PV_{Gradient}$ exceeding the Control group's $95\%CI_{Gradient}$ (lower bound, −0.11; upper bound, 0.12).

4. Discussion

Addressing the first aim to identify when changes in directly targeted BFb variables occurred, the breakpoint analysis on hip,

Table 1
Peak extension angular velocity for the hip, knee and ankle joints at each of the retention visits at weeks 4–6 ($Retention_{Wk4-6}$), 13 ($Retention_{Wk13}$) and 26 ($Retention_{Wk26}$). Data are percentage change from pre-intervention, and are means ± 95%CI. The 2 × 3 mixed ANOVA main effects and interaction are provided for each joint.

Joint	Visit	BFb group	Control group	Statistics	p
Hip	$Retention_{Wk4-6}$	30 ± 18*	5 ± 18	Group main effect	0.024ǂ
	$Retention_{Wk13}$	39 ± 23*	−2 ± 22	Time main effect	0.590
	$Retention_{Wk26}$	35 ± 21*	7 ± 20	Interaction	0.095
Knee	$Retention_{Wk4-6}$	24 ± 11*	−7 ± 11	Group main effect	0.001ǂ
	$Retention_{Wk13}$	24 ± 11*	−4 ± 10	Time main effect	0.094
	$Retention_{Wk26}$	25 ± 11*	0 ± 11	Interaction	0.274
Ankle	$Retention_{Wk4-6}$	27 ± 20*	−7 ± 20	Group main effect	0.027ǂ
	$Retention_{Wk13}$	32 ± 23*	−3 ± 23	Time main effect	0.972
	$Retention_{Wk26}$	34 ± 23*	0 ± 23	Interaction	0.120

* Signifies significant difference from pre-intervention ($p < 0.05$).
ǂ Signifies significant difference between BFb and Control groups ($p < 0.05$).

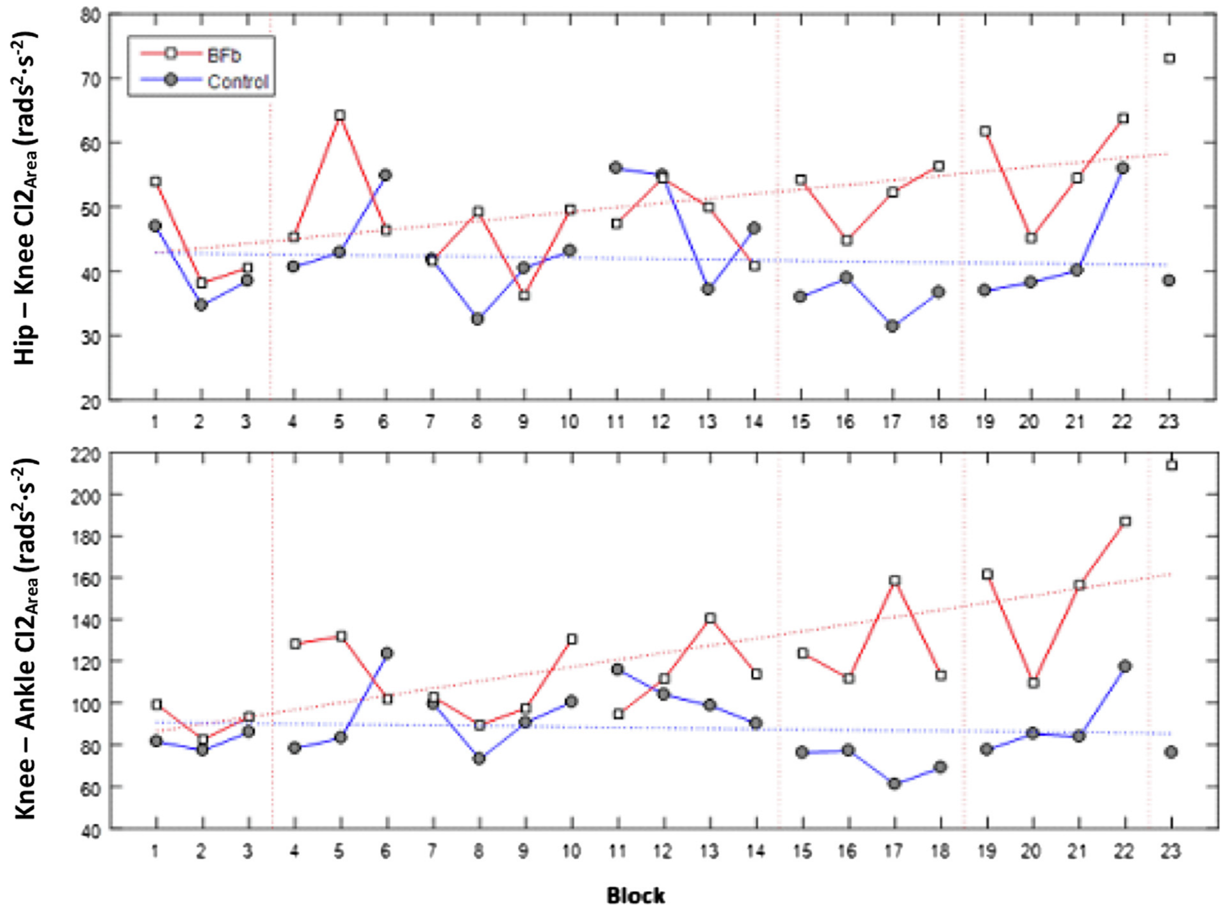

Fig. 6. Hip-knee (top) and knee-ankle (bottom) coupling coordination variability ($CI2_{Area}$) profiles for biofeedback (BFb) and Control groups over 23 blocks, spanning 26 weeks. The vertical red dashed lines separate between sessions (Self learning, Intervention, 4–6 weeks, 13 weeks and 26 weeks). Dashed lines are simple linear regressions fitted to each group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Individual changes in coordination variability gradients ($CV_{Gradient}$) determined from coordination variability ($CI2_{Area}$) for BFb group hip-knee and knee-ankle couplings.

	Hip-Knee $CV_{Gradient}$		Knee-Ankle $CV_{Gradient}$	
BFb Participant #	Control	BFb	Control	BFb
1	0.26	5.13*	−0.19	18.97*
2	0.09	0.54	0.05	10.39*
3	0.39	1.58*	1.43	1.64
4	−0.17	0.49	−0.15	−3.46
5	−0.11	−0.81	−0.88	−1.05
6	0.95	−0.10	3.28	−1.51
7	−1.94	1.58*	−7.90	12.54*
8	−0.12	1.26*	1.44	−0.56
9	1.33	2.24*	−0.12	4.97*
10	−0.43	−0.06	−0.62	3.40*
11	−1.46	−1.62	−3.49	−3.53
12	−0.54	−0.02	0.29	−1.56
13	−0.37	1.62*	3.34	6.37*
14	−0.05	−0.80	−1.42	1.83*
15	1.67	1.34*	0.54	7.80*
Control Group	**95%CI Upper**	1.21	**95%CI Upper**	1.72
	95%CI Lower	−0.79	**95%CI Lower**	−0.07

* Signifies BFb individuals with $CV_{Gradient}$ greater than Control group's 95%CI upper bound of their $CV_{Gradient}$.

knee and ankle angular velocity changes shows that the visual feedback design used in this research was effective, with athletes attending to the BFb and showing a plateau in motor development within just two sessions (Fig. 5). Kinematic changes occurring following just one visit of BFb have been shown in both continuous (Crowell et al., 2010; Baggaleley et al., 2017) and discrete skills (e.g. squatting; Ford et al., 2015). However, without retention testing in these studies it is not possible to confirm that changes were maintained. With changes occurring early on, the present study also highlights that complex BFb information given to participants can encourage changes in technique, but without distracting participants from important sources of internal information (Park et al., 2000). Encoding complex data into a simple presentation, with the addition of transitional information on how to alter performance, helps enhance BFb effectiveness (Kernodle and Carlton, 1992). For all three joints' peak extension angular velocities, the Control group did not change from pre-intervention to any of the three retention visits ($p > 0.05$). In contrast, the BFb group significantly improved by the $Retention_{Wk4-6}$, and this improvement remained for the further $Retention_{Wk13}$ and $Retention_{Wk26}$ visits ($p < 0.05$). This improvement in the BFb group shows that the kinematic changes induced were relatively permanent. This learning supports that there was no dependency from a reducing BFb schedule where BFb was delivered with ever increasing time between visits. A reducing schedule is thought to foster cognitive strategies through mental rehearsal, with sufficient time between visits enhancing cognitive processing (Thorpe and Valvano, 2002). Intelligent BFb scheduling, paired with a reducing schedule, may therefore be an effective method in the long term to avoid dependency effects of BFb while still allowing a large volume of information to be used to induce specific changes in a complex skill.

The skill adaptations shown within just two sessions highlight how effective knowledge of performance BFb can be when used appropriately. The feedback specifically guides an individual on how to achieve a desired movement related to their performance, which is increasingly important when a specific technique is the focus of an intervention. Allowing a system to self-organise rather than defining constraints (e.g. kinematic patterns) may be more useful in some cases, such as in novice motor learning (e.g. Wulf et al., 2010), however not necessarily as beneficial when attempting to direct specific movement patterns as in rehabilitation (e.g. van den Heuvel et al., 2016). Although changes occurred quickly, it is important to consider the influence of BFb on more permanent learning for real world applications, particularly during a reducing BFb paradigm.

Addressing the second aim to apply a new measure of $Coord_{Var}$ to explore skill exploration, the results demonstrate that $CI2_{Area}$ was effective in identifying changes in $Coord_{Var}$ of the hip-knee and knee-ankle joint couplings between a Control group and a skill development BFb intervention group. Importantly, these findings were demonstrated in a complex skill involving the whole lower limb, making it potentially applicable to other real-world skills. Using results from $CI2_{Area}$, it can be ascertained that the BFb intervention does indeed guide skill exploration as suggested in previous research (Lauber et al., 2013). The continual increase in $CI2_{Area}$ also highlights the increasing exploration throughout the six-month intervention period, which supports that a reducing BFb schedule does not lead to dependency whereby exploration ceases. Quantification using $CI2_{Area}$ also allows for the mapping of motor learning theory to applied practice. According to Bernstein's (1967) stages of motor learning, participants in this research can be seen continually freeing the coordinated degrees of freedom to explore task execution evidenced by the increasing $Coord_{Var}$. This is also in line with concepts proposed by Newell (1985) in that the BFb group were self-organising hip-knee and knee-ankle joint couplings to satisfy task constraints of the skill in achieving maximal CoM propulsion, but had not fully gained control of the complex motor skill to converge on a stable pattern. In this respect, $CI2_{Area}$ values could be used to indicate when changes to the intervention may have been required to better facilitate the development of a more stable $Coord_{Var}$ pattern. Therefore, perhaps more BFb would have helped to solidify learning, although it is difficult to establish this without using $CI2_{Area}$ results to manipulate schedules mid-intervention. In future, $CI2_{Area}$ could be applied to assess changes of $Coord_{Var}$ in real-time. It can be postulated that the low volume of BFb (six hours per individual) kept BFb participants in a continual state of exploration. However, questions do arise as to when this increase would plateau, or even reduce, as prescribed in Bernstein's (1967) and Newell's (1985) theoretical frameworks. These paradigms both suggest that $Coord_{Var}$ may decrease as a skill is mastered but would still allow functionally variable interactions to maintain a stable and successful performance outcome as seen with $Perf_{Var}$ remaining consistent in both groups. Future research should seek to identify changes of $Coord_{Var}$ using $CI2_{Area}$ in comprehensive, complex-skill, motor learning interventions to provide more comparative data to map learning to stages of learning.

Importantly, $CI2_{Area}$ was able to identify the individual responses to the skill intervention. The importance of individualised approaches is evident in clinical practice and high-performance sport (e.g. Needham et al., 2018; Glazier and Mehdizadeh, 2018). Relative to the Control group's hip-knee $CI2_{Area}$ over the six months, 7 out of the 15 BFb group's individual $CV_{Gradient}$ were greater than the Control group's upper $95\%CI_{Gradient}$. Almost half of the BFb group explored the rear leg propulsion pattern by increasing hip-knee coupling exploration strategies. In addition, 8 out of 15 BFb individuals had knee-ankle coupling $CV_{Gradient}$ which exceeded the upper $95CI\%_{Gradient}$ of the Control group. This is in line with previous research underpinning whole limb sequential coordination strategies, with the more distal joints offering a compensatory strategy for movement errors in more proximal segments (Robins et al., 2006; Mullineaux and Uhl, 2010). Looking at both joint couplings across individuals, the same 5 individuals (Table 2) had both hip-knee and knee-ankle coupling variability greater than the control group. This also seems to suggest that certain individuals have greater $Coord_{Var}$, which may be a strategy underpinning motor learning effectiveness and supports the importance of exploring individuals' approaches to skill development.

5. Limitations

The main limitation that became apparent following the intervention is how quickly the individuals satisfied the task to cover a distance of 1.5 times leg length. The distance was fixed to maintain scientific control but in future a progression in task complexity should be incorporated. This may have inhibited further increases in performance, as individuals felt the target was too close at the end of the intervention week. This, paired with continually increasing $Coord_{Var}$ suggests participants were still exploring the skill over 26 weeks. The joint definitions within this study were chosen as they required a small number of anatomical landmarks which may assist in any future development of BFb devices. However, as these definitions, including that the hip joint definition is a segment definition, may influence the proximo-distal sequencing and $Coord_{Var}$ calculations in an undesirable manner. Through BFb there was an increase in both joint angular velocity and $Coord_{Var}$, and partitioning out the causal variance component of this relationship needs exploring. Methodologically, $CI2_{Area}$ provides a robust measure, however further work is required to verify the validity of whether an increase or decrease in $Coord_{Var}$ is reflective of changes in motor learning.

6. Conclusion

Directly targeted kinematic variables can be altered using BFb within just two sessions in a complex, whole limb skill. The use of a longitudinally reducing BFb schedule was effective in avoiding dependency properties of BFb, demonstrated with no significant reduction in skill during retention tests over 26 weeks. A new approach to assess coordination variability using $CI2_{Area}$ was effective in identifying group and individual skill exploration strategies and can be explored in the future to map individual exploration strategies to the stages of motor learning.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the content of this article.

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