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Intra- and inter-subject variation in lower limb coordination during countermovement jumps in children and adults

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ABSTRACT

The purpose of the present study was to investigate the coordination pattern and coordination variability (intra-subject and inter-subject) in children and adults during vertical countermovement jumps. Ten children (mean age: 11.5 ± 1.8 years) and ten adults (mean age: 26.1 ± 4.9 years) participated in the experiment. Lower body 3D-kinematics and kinetics from both legs were obtained during 9 vertical jumps of each subject. Coordination pattern and coordination variability of intra-limb and inter-limb coupling were established by modified vector coding and continuous relative phase. The adult group jumped higher and with less performance variability compared to the children. Group differences were mainly observed in the right–left foot coupling. The intra-subject coordination variability was higher in coupling of proximal segments in children compared to adults. No group differences were observed in inter-subject variability. Based on these results, it was concluded that the same movement solutions were available to both age groups, but the children were less able to consistently utilize the individually chosen coordination pattern. Thus, this ability appears to be developed through normal ontogenesis.

1. Introduction

During human movements the multiple degrees of freedom in the body is reduced through coordination of muscle synergies across one or several joints (Turvey, 1990) and this coordination is continuously challenged and gradually changed with maturation and skill learning (Thelen, 1995). From a Dynamical System Theory point of view particular behavioural configurations of biomechanical components form movements (different types of skills). Changes in the number of configurations and the stability of the configuration can be caused by changes in the biomechanical constraints related to maturation, ageing, training or disorders or by changes in the constraints related to the task and the environment (Newell & Vaillancourt, 2001; Thelen, 1995).

Bernstein stated that no movement could be completely replicated due to the redundant number of degrees of freedom of the moving human body (Bernstein, 1967). This inherent variability has been addressed differently in the motor control and biomechanical literature. A traditional motion analysis approach often disregards the intra-subject movement variability and considers it to be unimportant biological noise in the human movement system. Dynamical System Theory considers intra-subject variability as important information about the stability of the behavioural attractor state of the system. During childhood development of walking, stable behavioural attractor states with low movement variability has been associated with

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different maturation states. Unstable behavioural attractor states with higher movement variability has been associated with the nonlinear transition between walking skill levels observed at different maturation stages (Thelen & Ulrich, 1991). In addition, Bernstein suggested that motor learning is characterized by three steps of freezing and freeing the redundant number of degrees of freedom (Bernstein, 1967). First, the unstable and variable behavioural attractors at the novice stage moves towards a stable and controllable stage with less variability (freezing). Second, to explore and expand the controlled attractors constraints are lifted and the variability increased. Thirdly, the movements are optimized by increased use of passive structures. These stages have been linked with both maturational motor learning in infants (Harbourne & Stergiou, 2003), motor learning (Newell & Vaillancourt, 2001) and skill learning in sports (Handford, Davids, Bennett, & Button, 1997).

In contrast to walking, vertical jumping tasks like a countermovement jump is a discrete task with a distinct start and end and no continuous cyclic pattern. In similarity to walking and running, countermovement jumps involve bilateral coordination of lower limbs and precise positioning of the upper body to maintain balance during both the take-off, flight and landing phases. Unless involved in jump specific sports events, few children and adults will train the execution of a countermovement jump in their everyday life, and the jumping performance of such individuals will grossly reflect a developmental level of whole-body coordination. Developmental stages have been linked to differences in knee–hip joint coordination and range of knee flexion during vertical jumps in children (Harrison, Ryan, & Hayes, 2007; Ryan, Harrison, & Hayes, 2006). Harrison et al. (2007) observed that children with a more mature jumping pattern were characterized by more knee flexion and less hip flexion compared to less mature subjects. The authors suggested that maturation was linked with an increasing use of stretch-shortening cycle in the knee extensor muscles. In addition, Ryan et al. (2006) observed a large variability in earlier maturation stages compared to later stages in children, which could be explained as a developmental change from unstable and more variable attractors to more controlled and less variable behavioural attractors. Both Harrison et al. (2007) and Ryan et al. (2006) used variation within groups of children at different maturation stages (inter-subject variation). Thus, the variation within multiple executions of vertical jumps in each subject (intra-subject variation) was not addressed in the mentioned studies. A decrease in inter-subject variation with maturation could indicate a development of a universal movement solution for vertical jumps. However, comparing the variation in performance level (e.g. variation in jumping height) and the intra-subject variation could reveal information about the efficiency of the movement solutions utilized by the individual subjects. In sitting and standing balance intra-subject variation has been observed to decrease with developmental stage (James, Hong, & Newell, 2009; Wu, McKay, & Angulo-Barroso, 2009). In relation to the learning curve suggested by Bernstein (1967), a novice stage would be characterized by high performance variation and higher intra-subject variation, a trained stage by low performance variation and low intra-subject variation and a skilled stage by low performance variation and high intra-subject variation. In the present study, we applied this combination of the performance variation (coefficient of variation of the jumping height) and the intra-subject variation to investigate the efficiency of the utilized movement solution by children and adults during vertical jumps. Furthermore, we quantified inter-subject variability to investigate if adult subjects tend to have a more universal and uniform movement pattern compared to children.

It has been suggested that the coordination pattern can be described by the *state space* of selected coordinative parameters (e.g. movement of segments or joints (Kelso, 1995)). Quantifying the coupled movement of segments in *state space* provides more detailed information of the coordination than simple linear or angular motion data from each segment separately (Kurz & Stergiou, 2004). Methods such as modified vector coding and continuous relative phase can be applied to kinematic signals to quantify the segmental coordination (Davids, Glazier, Araujo, & Bartlett, 2003; Preatoni et al., 2013). These methods have been used to study the coordination pattern and coordination variability related to development (ontogenesis) (Vereijken & Thelen, 1997), skill learning (Vereijken, Van Emmerik, Bongaardt, Beek, & Newell, 1997), injuries (Hamill, Palmer, & Van Emmerik, 2012; Hamill, van Emmerik, Heiderscheit, & Li, 1999; Heiderscheit, Hamill, & Vereijken, 2002), and individuals with different skill levels (Wilson, Simpson, van Emmerik, & Hamill, 2008).

Modified vector coding is a measure of the continuous dynamic interaction between two segments and quantified by the vector orientation relative to the horizontal line between two adjacent data points in time in an angle–angle diagram (Hamill, Haddad, & McDermott, 2000; Needham, Naemi, & Chockalingam, 2014). The outcome measure is a coupling angle between 0° and 360° and providing information of the degree of coupling between segment angles. Modified vector coding has been used to quantify the coordination variability during gait (Needham et al., 2014; Sparrow, Donovan, van Emmerik, & Barry, 1987), running (Heiderscheit et al., 2002) and jumping (Wilson, Simpson, & Hamill, 2009; Wilson et al., 2008). The method is limited by only combining the spatial information (segment angle) and does not include the temporal information (segment angular velocity).

Continuous relative phase quantifies the movement of two segments based on the difference in their phase plane angle and it describes a higher order measure of coordination of the segments (Preatoni et al., 2013). Prior to calculating the continuous relative phase, the movement dynamics of each segment in question is illustrated in a phase plane by plotting segment angle velocity against segment angle. The representation of each segment in phase plane is quantified by the phase angle between the vectors from origin to the Cartesian coordinates of each data point in time and the horizontal axis. Continuous relative phase is calculated as the difference between the phase angles of two segments (Clark & Phillips, 1993; Hamill et al., 1999). The continuous relative phase contains both spatial and temporal information of the coordination of segments and has been used to quantify the coordination and coordination variability of segments in lifting (Burgess-Limerick, Abernethy, & Neal, 1993), walking (Burgess-Limerick et al., 1993; Li, van den Bogert, Caldwell, van Emmerik, & Hamill, 1999), ski jumping (Chardonnens, Favre, Cuendet, Gremion, & Aminian, 2013) and running (Hamill et al., 1999; Li et al., 1999;