MOVEMENT PROTOTYPES IN THE PERFORMANCE OF THE HANDSPRING ON VAULT

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Original article

Abstract

Most research concerning the kinematic analysis of gymnastics skills only deals with selected variables, thereby often ignoring the holistic nature of the analyzed skills. Therefore, the goal of this study was to develop an innovative approach to analyze the front handspring on vault. To gain comprehensive insight into the aforementioned motor skill, different skill prototypes should be detected and their variant and invariant characteristics should be investigated. The digitized video sequences of 60 handspring trials from ten female gymnasts were used for kinematic analysis. Time courses of six joints were analyzed by means of a hierarchical cluster analysis. In addition, the coefficients of variation were calculated. Results revealed that four distinct prototypical movement patterns could be identified for the handspring on vault in female near-expert gymnasts. The movement patterns within each prototype are thereby more similar to each other than the movement patterns between the four prototypes. The four different prototypes can be distinguished by certain variant and invariant characteristics, that become obvious when inspecting the time courses of the hip and shoulder angles, as well as the time course of the coefficient of variation. In light of the training process in gymnastics, the study provides further evidence for strongly considering gymnasts' individual movement patterns when it comes to motor skill acquisition and optimization.

Keywords: *kinematic analysis, cluster analysis, prototypical movement patterns, variant and invariant characteristics.*

INTRODUCTION

Artistic Gymnastics involves very complex and technically demanding sequences of elements requiring maximal effort and a high level of functional ability such as agility and coordination (Arkaev & Suchilin, 2004). There is a large number of studies in the field of sport science and gymnastics investigating biomechanical aspects of different gymnastics elements (Prassas, Kwon, & Sands, 2006). However, the evaluation of gymnastics performances during training and competition mainly relies on observation by coaches or judges, and is therefore influenced by their respective perception of different kinematic characteristics (Bradshaw & Sparrow, 2001; Farana, Uchytil, Zahradník, & Jandacka, 2015; Farana & Vaverka, 2012). Due to the presence of the high amount of degrees of freedom in the human motor system, movements can be performed in many different ways (Bernstein, 1967; Latash, Scholz, & Schöner, 2002). Because humans perceive movement in a holistic way (Davids et al., 2014; Jeraj, Hennig, & Heinen, 2015; Johansson, 1973), the interrelation of movement characteristics with the evaluation can only take place when a movement is taken into account as a whole, and not as a collection of individual parameters. The goal of this study was to identify different prototypes and their variant and invariant characteristics by means of an innovative approach that allows to analyze gymnastics skills in a holistic fashion.

Theoretical Background

When engaged in a goal-directed activity, like a handspring on vault, performers develop different coordination states through learning and practice (Davids, Button, & Bennett, 2008). Those coordination states are not constantly stable but contain a particular amount of variability leading to distinguishable movement options that could be described by a specific composition of biomechanical parameters (Latash et al., 2002). Gymnastics skills can be seen as complex systems. Complex systems consist of many components, which interact among themselves and as a whole with the environment. These interactions change depending on the constraints embedded within the complex system and without being previously developed and imposed on the systems behavior (Davids et al., 2014). The functional role of movement variability in human motor behavior was emphasized in the works of Bernstein (1967) and Higgins (1977) and through nonlinear statistical models in the study of human movement systems (Thompson & Stewart, 2002). It is thought that variation in the structure or function of complex biological systems, interacting with different constraints provided by the task, the environment or psychological factors, leads to movement variability (Davids et al., 2008; Higgins, 1977).

There is recent evidence from empirical research that movement variability is an essential feature of human motor behavior. It affords the necessary flexibility and adaptability to operate proficiently in a variety of performances in fine and gross motor skills (Fitzpatrick, Schmidt, & Lockman 1996; Kelso, 1995; Li, van den Bogert, Caldwell, van Emmerik, & Hamill, 1999), and also for complex skills in gymnastics comprising whole-body rotations (Hiley, Wangler, & Predescu, 2009; Williams, Irwin, Kerwin, & Newell, 2015). This movement variability and the resulting coordination dynamics in complex systems have a tendency to form patterned behavior (synergies) which have time-dependent characteristics (Davids et al., 2014).

Nowadays a large amount of kinematic and kinetic data is available to describe human movement. However, sports scientists usually identify, measure, and interpret selected variables, especially on the basis of time discrete values of selected variables (Federolf, Reid, Gilgien, Haugen, & Smith, 2014; Young & Reinkensmeyer, 2014). Schöllhorn, Chow, Glazier, and Button (2014) illustrated the difference between time discrete and time continuous movement with the following analogy:

If we see a known person far away standing still, it is often difficult to identify that person. Once he/she starts to walk, our visual system receives additional information that increases the likelihood of recognizing that person." (Schöllhorn et al., 2014, pp. 145).

Perception appears to be a complex process with a holistic character that takes into consideration hints and cues that are distributed over the whole time and space, in which the movement is performed and which is carried both by movement-mediated structural information and by pure dynamics (Troje, 2002). There is further evidence that the perception of biological movement relies on relative movement rather than absolute movement characteristics (Johansson, 1973). Especially in gymnastics, movement is described by coaches, judges, and athletes in terms of specific body postures and movement components (Jeraj et al., 2015). Nevertheless, the challenge is to find an appropriate approach to analyze the holistic nature of gymnastics skills.

Quantitative technique analysis seems not suitable for establishing the characteristics of the whole skill, but methods, such as cluster analysis or principal component analysis may be able to overcome this limitation (Davids et al., 2014; Lees, 2002). Plausible criteria for a classification of objects seem to be their relative similarity or proximity of movement characteristics. The simplest procedure of classifying objects is to quantify certain characteristics of all objects and to determine the relative distance of these quantities. Joint and body angles seem to be such characteristics because they can be used to describe gymnastics skills in a holistic way, and other kinematic characteristics can easily be computed from these values (Enoka, 2002).

Hence, qualities can be compared by means of their relative size or vector distance. A commonly used measure for mathematical comparisons is the euclidean distance, which represents the mathematical distance between two objects. Cluster analysis then deals with the quantitative sorting of these euclidean distances (Everitt & Dunn, 2001). If for example the euclidean distance between the knee angles of two participants, performing a handspring on vault, is smaller than the euclidean distance relative to a third participant, the first two participants would be assigned to one cluster and the third participant to another cluster. Thus, clustering aims to find groups of objects with a high degree of structural similarity to each other, which can be visualized in a tree diagram. Given the natural variation of objects in relation to their analyzed qualities, the different clusters contain a certain degree of variability (Troje, 2002). In this study, the goal was the identification of prototypical movement patterns of the handspring on vault by means of a cluster analysis. A prototype is thereby defined by the average angle-time courses of all trials which are assigned to one cluster.

Objectives and Hypothesis

It can be stated that for a better understanding of complex gymnastics performances it is not only relevant to analyze isolated parameters, but to analyze gymnastics skills in a holistic way. Relevant criteria for a classification of objects seem to be their relative similarity or proximity of kinematic characteristics like particular joint and body angles. Until now, there is a lack of gymnastics research, which deals with analyzing gymnastics skills holistically. Thus, the purpose of this study was to examine gymnastics performance in a holistic way based on an explorative approach of analyzing time continuous data. Special interest was on two topics: (a) to identify prototypes of a gymnastics skill, and (b) to explore the structure of a gymnastics skill in terms of its variant and invariant characteristics.

In a first step, the angle-time courses of separate trials of one specific gymnastics skill (handspring on vault) were mathematically analyzed with a cluster analysis. It was hypothesized that some trials are more similar than others. The cluster analysis should reveal patterns of similarity, leading to a particular number of distinguishable clusters (i.e. *prototypes*). In a second step the variant and invariant characteristics were investigated qualitatively by analyzing the angle-time courses in relation to the different prototypes and the different movement phases. It was hypothesized that the prototypes differ in their variant and invariant characteristics in specific movement phases.

METHODS

Participants

Ten female gymnasts participated in this study (age: M = 11.50, SD = 1.43; body size: M = 143.00 cm, SD = 11.36 cm). The gymnasts reported an average training amount of 26 hours per week. They were able to perform the experimental task of this study with a high degree of consistency in training and competition (handspring on vault; see Motor task section).

Motor task

The motor task was a handspring on vault (Čuk & Karácsony, 2004). The vaulting table was arranged according to the competition guidelines of the International Gymnastics Federation for women's artistic gymnastics (FIG, 2017). There was a running track in front of the table, landing mats (0.20 m high) behind the table, and a certified springboard (1.20 m long and 0.60 m wide) in front of the table. The vaulting table was adjusted to a height of 1.25 m.

The handspring on vault can be subdivided into six movement phases: approach run and hurdle, take-off phase, first flight phase, repulsion phase, second flight phase, and landing phase (Brüggemann, 1994). From a standing position at the beginning of the running track, the gymnast performs an accelerated run-up towards the vault apparatus. A hurdle motion at the end of the run-up precedes a reactive leap on the springboard, which in turn precedes the first flight phase to support on both hands on the vaulting table. During support, the gymnast pushes of the vaulting table, and performs a whole-body rotation about the somersault axis during the subsequent flight phase. The handspring ends with a landing on both feet in upright body posture. Gymnasts were asked to perform handsprings on vault as they would do in a regular competition. In particular they were asked to perform handsprings with the highest movement quality they were capable of at the time of the study.

Movement Analysis

The performance of the gymnasts was videotaped with a digital video camera (240 Hz, 1920 x 1080 pixel) which was placed at a distance of about 15 m from the vaulting table in order to compensate for lens distortion. The camera videotaped gymnasts' performance orthogonal to the movement direction, simulating the judge's perspective. For the kinematic analysis, the recorded video sequences were used. The horizontal and vertical coordinates of 18 points (body landmarks) were digitized for each frame using the movement analysis software Simi Motion®. Thus each one of the 18 body landmarks was represented by a two-dimensional time series $[x_j(t); y_j(t)]$ with j = 1, 2, 3, …, j (t = time, j = frame number). The 18 body landmarks defined a 17-segment model of the human body (Enoka, 2002). A software built-in digital filter was applied for data smoothing. For each trial, the time series of each body landmark was time normalized and rescaled to the interval [0; 1000]. Kinematic angular data were calculated from the time-normalized position data of the body landmarks for all handspring trials (Jaitner, Mendoza, & Schöllhorn, 2001). The calculated joint angles (knee, hip, shoulder) were specified with regard to the frontal horizontal body axis, thereby reflecting flexion and extension movement (Behnke, 2001).

Procedure

The study was conducted in three phases. In the first phase the gymnast arrived at the gymnasium. She was informed about the general procedure of the study. In particular, the gymnast was told that she takes part in a study on kinematic analysis of the handspring on vault. The study was conducted in compliance with the Helsinki Declaration and the International Principles governing research on humans, as well as in line with the ethical guidelines of the local ethics committee. The gymnast gave her informed consent, and was given a 20-minute warm-up period. After warm-up, the gymnast was allowed one familiarization trial. In the second phase, the gymnast performed ten handsprings on vault. She was allowed to take breaks as requested and there was no time pressure. In the third phase, and after completing the ten handsprings on vault, the gymnast was debriefed and dismissed into an individual cool-down period.

Data Processing and Analysis

The free statistic software R (R Core Team, 2017) was used for further data processing and analysis. The further data analysis comprised two steps: In a first step, the prototypical movements of the handspring on vault were identified by means of a hierarchical cluster analysis. Therefore, euclidean distances were calculated for each time course of joint angles (see equation 1: *x* and *y* denote a corresponding joint angle between a pair of two handsprings and *i* denotes a point in the rescaled time interval [0;1000]). The resulting values were summed up to form one euclidean distance value for each pair of two handspring trials. Thereby a value of zero would have indicated an exact identical course of two handspring trials whereas the larger the resulting value, the more dissimilar two trials were.

Equation 1: $d(x,y) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}$

The resulting euclidean distance values were recorded to a distance matrix, indicating the similarity between each pair of two handspring trials. In order to classify all trials by means of their similarity, the euclidean distance matrix was evaluated quantitatively by a hierarchical cluster analysis using Ward's hierarchical clustering method (Ward, 1963). It was decided to use Ward's method because this is an agglomerative clustering method that is based on a classical sum-of-squares criterion, producing groups that minimize within-group dispersion at each fusion step (Murtagh & Legendre, 2014). The classification result was represented by a two-dimensional tree diagram illustrating the fusions or divisions made at each stage of the analysis. The number of clusters was determined by inspecting the scree plot in terms of the elbow criterion (Everitt & Dunn, 2001). In a second step and in order to characterize each of the prototypes, the time courses of the joint angles were averaged over the corresponding trials in each cluster. In addition, the time courses of the coefficient of variation were calculated for all joint angles of each prototype, indicating the relative extend of variability of a particular prototype along its time course (Stergiou, 2004).

RESULTS

Figure 1 presents the result of the hierarchical cluster analysis. Four subgroups (i.e., clusters) could be distinguished from each other following the inspection of the scree plot of the cluster analysis. Each of the four clusters thus comprised handspring trials that were more similar to trials within a particular cluster, but which were more dissimilar to handspring trials in the other clusters. Therefore, each cluster characterized a particular handspring prototype within the sample of all analyzed handspring trials. Inspecting the individual clusters revealed that prototype #a comprised 17 handspring trials (28.33%), and prototype #b comprised 15 (25%) handspring trials. Prototype #c contained 7 handspring trials (11.67%), and prototype #d contained 21 handspring trials (35%). A subsequent Chi-square test revealed a statistical trend that the amount of handspring trials was not distributed equally between the four clusters, $\chi^2 = 6.93$, $p = .07$, indicating that some handspring prototypes appear more frequently in gymnasts, such as prototype #d, while other prototypes appear less frequently, such as prototype #c.

Prototype 1

In cluster #a, 17 trials were grouped together. A picture sequence of an exemplary trial can be seen in Figure 3a. Exemplary time courses of hip and shoulder joints can be found in Figure 2a and 2b. A typical handspring trial from cluster #a comprised the following characteristics: 1) slightly inclined trunk with open shoulder angle during touch-down on springboard, 2) inclined trunk, slightly flexed hip joint and open shoulder angle during take-off from the springboard, 3) slightly flexed hip joint, open shoulder angle and trunk orientation close to 45° during touch-down on the vaulting table, 4) slightly overarched back, and stretched hip and shoulder joints during take-off from the vaulting table, and 5) straight back with slightly flexed hip and knee joints and open shoulder angle during touch-down on the landing mat. There was a rather small coefficient of variation for the hip joint and the knee angle over the time course (0 - 0.1). For the shoulder angle, the coefficient of variation was about 0.2 at the take-off phase which decrease to 0.1 during the first flight phase. Exemplary time courses of the coefficient of variation of hip and shoulder joints for the four prototypes can be found in Figure 2c and 2d.

Prototype 2

In cluster #b, 15 trials were grouped together. A picture sequence of an exemplary trial can be seen in Figure 3b. Exemplary time courses of hip and shoulder joints can be found in Figure 2a and 2b. A typical handspring trial from cluster #b comprised the following characteristics: 1) upright trunk orientation with shoulder angle slightly larger than 90° during touch-down on springboard, 2) inclined trunk, slightly flexed hip joint and open shoulder angle during take-off from the springboard, 3) slightly extended hip joint, slightly flexed shoulder joint and trunk orientation close to 45° during touch-down on the vaulting table, 4) considerable overarched back, stretched hip and shoulder joints during take-off from the vaulting table, and 5) straight back with slightly flexed hip and knee joints and open shoulder angle during touch-down on the landing mat. There is a small coefficient of variation for the hip angle and the knee angle over the whole movement (below 0.1). The shoulder angle showed a larger coefficient of variation (about 0.15) at the take-off phase, the beginning of the first flight phase, the end of the second flight phase and the landing phase and a coefficient of variation about 0.1 at the rest of the movement. Exemplary time courses of the coefficient of variation of hip and shoulder joints for the four prototypes can be found in Figure 2c and 2d.

Prototype 3

In cluster #c, 7 trials were grouped together. A picture sequence of an exemplary trial can be seen in Figure 3c. Exemplary time courses of hip and shoulder joints can be found in Figure 2a and 2b. A typical handspring trial from cluster #c comprised the following characteristics: 1) upright trunk orientation with shoulder angle less than 90° during touch-down on springboard, 2) inclined trunk, slightly flexed hip joint and shoulder angle greater than or equal to 90° during take-off from the springboard, 3) slightly flexed hip joint, flexed shoulder angle and trunk orientation angle smaller than 45° during touch-down on the vaulting table, 4) considerable overarched back, stretched hip and flexed shoulder joints during take-off from the vaulting table, and 5) slightly overarched back with stretched hip and knee joints and open shoulder angle during touch-down on the landing mat. In terms of the variation of the movement for the different trials, there is a low coefficient of variation for all joint angles over the time course (0 - 0.1). Exemplary time courses of the coefficient of variation of hip and shoulder joints for the four prototypes can be found in Figure 2c and 2d.

Prototype 4

Finally, in cluster #d, 21 trials were grouped together. A picture sequence of an exemplary trial can be seen in Figure 3d. Exemplary time courses of hip and shoulder joints can be found in Figure 2a and 2b. A typical handspring trial from cluster #d comprised the following characteristics: 1) upright trunk orientation with shoulder angle larger than 90° during touch-down on springboard, 2) inclined trunk, slightly flexed hip joint and shoulder angle greater than 90° during take-off from the springboard, 3) slightly flexed hip joint, open shoulder angle and trunk orientation slightly greater than 45° during touch-down on the vaulting table, 4) straight back, trunk orientation about +10° from vertical, stretched hip and shoulder joints during take-off from the vaulting table, and 5) straight back with slightly flexed hip and knee joints and open shoulder angle during touch-down on the landing mat. In terms of the variation of the movement for the different prototypes, the knee angle shows a coefficient of variation of 0.2 at the take-off which decreased until nearly zero at the end of the first flight phase. There was a small coefficient of variation for the hip angle(0 - 0.1) over the time-course. For the shoulder angle, the coefficient of variation was about 0.2 at the take-off phase and decreased to 0.1 during the first flight phase. Exemplary time courses of the coefficient of variation of hip and shoulder joints for the four prototypes can be found in Figure 2c and 2d.

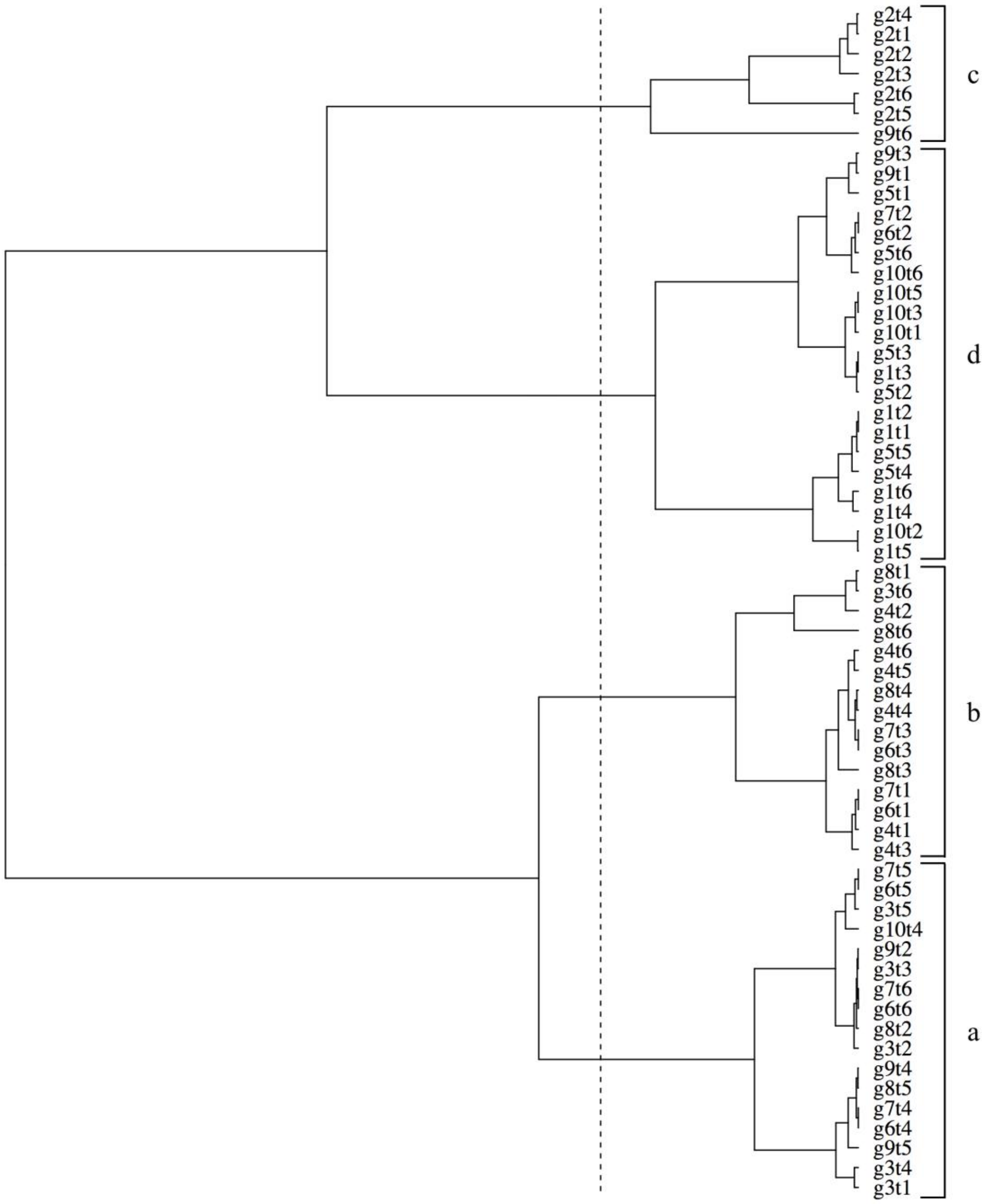

Figure 1. Tree diagram resulting from a cluster analysis using Wards' clustering algorithm. Horizontal lines indicate the level of the distance at which the respective handspring trials are grouped into one cluster. *Notes:* The dashed line represents the euclidean distance below which the clusters are identified. The letters "a)" to "d)" correspond to the four clusters, containing the different prototypical movement patterns of the handspring on vault. *g1t1* to *g10t6* represent the analyzed handspring trials.

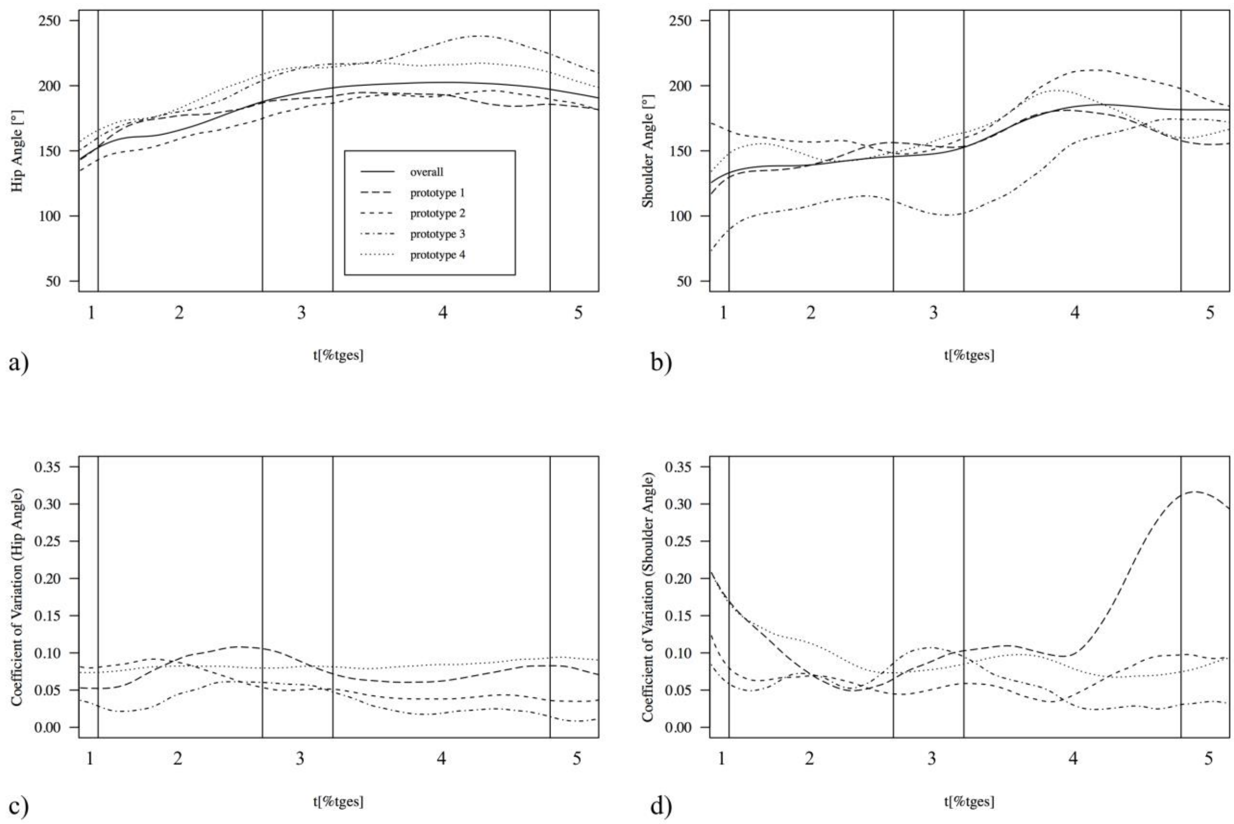

Figure 2. Illustration of time-normalized angle-time plots for the prototypical courses of the shoulder angle (a) and hip angle (b), as well as time courses of the corresponding coefficients of variation for the different prototypes (c, d). *Note:* 1 = take-off phase from springboard, 2 = first flight phase, 3 = repulsion phase, 4 = second flight phase, 5 = landing phase.

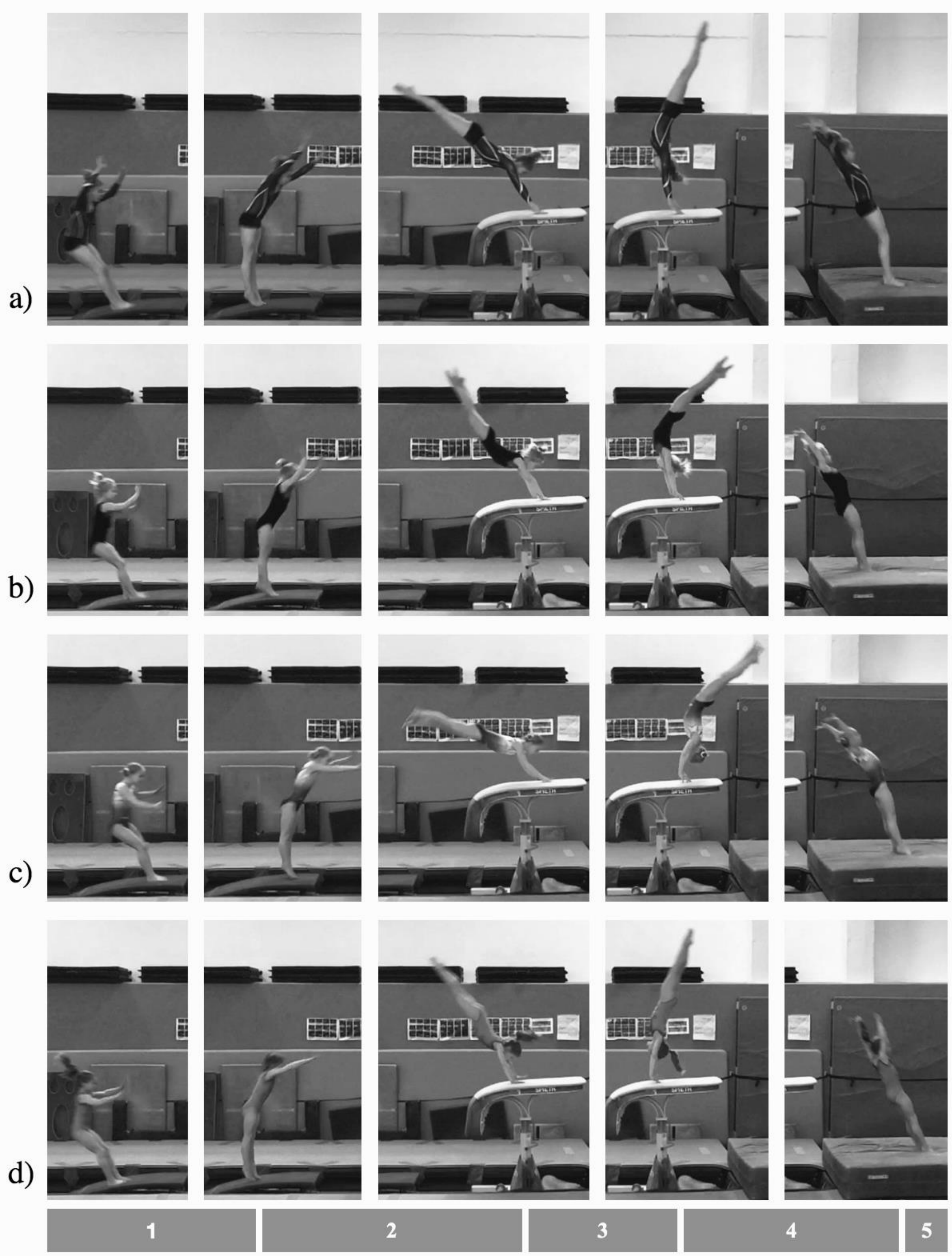

Figure 3. Illustration of the four handspring prototypes (see also Figures 1 and 2). a) Prototype #1, b) Prototype #2, c) Prototype #3, d) Prototype #4. *Note:* Each picture sequence shows one exemplary handspring trial of each prototype cluster. The letters "a)" to "d)" correspond to the four clusters in Figure 1. The number "1" to "5" correspond to the movement phases of the handspring (see Figure 2).

DISCUSSION

Most of the research concerning the kinematic analysis of gymnastics skills deals with selected variables. Because humans perceive movement in a holistic way, the goal of this study was to develop a method to analyze a front handspring on vault in a holistic fashion. To gain insight into a complex motor skill like the handspring on vault, different prototypes of the movements should be quantitatively detected and its variant and invariant characteristics should be qualitatively investigated. The results of this study revealed that for near-expert gymnasts four prototypical movement patterns could be identified. The four different prototypes can be differentiated by certain variant and invariant characteristics such as the time courses of the different joint angles and their coefficient of variation.

Concerning the assignments of the trials to one prototype one can see that the trials from one person are not assigned consistently to the four prototypes but rather most of them. This highlights that the pattern of movement characteristics stays similar over a high amount of trials, thus that there are structural similarities in space and time (Troje, 2002). When engaged in a goal-directed activity, like a handspring on vault, performers exhibit different coordination states. Those coordination states are not stable but contain variability leading to a set of movement options that could be described by a specific composition of biomechanical parameters (Latash et al., 2002). This instability might explain why not all trials of one gymnast are assigned to one prototype. Variations in the movement patterns are carried out through an interaction of the body as complex biological system with different constraints provided by the task, the environment or psychological factors leading to movement variability (Higgins, 1977).

Comparing the description of the four prototypes with the Code of Points (FIG, 2017), there are prototypes which meet the criteria for a high scoring and prototypes which might get deductions. According to the Code of Points (FIG, 2017), there are deductions for a poor technique regarding the hip, the shoulder and the knees. Out of the identified four prototypes, the movement patterns of prototype #a and prototype #d might meet the criteria the most. They are characterized by extended knees and hip and an open shoulder angle. The movement patterns of prototype #b and prototype #c might get the worst scoring.

There are limitations of this study and three specific aspects should be highlighted. First, looking at the tree diagram of the cluster analysis, one might assume that the trials could also be distributed into two, five or even six clusters. When analyzing the pattern of the movement characteristics it was revealed that by distributing the trials into two prototypes, a high number of structural features would be ignored, which could improve the description of the movement. On the other side, taking five or six prototypes would not improve the description of the movement. These findings are in line with the results given by the elbow method, which looks at the percentage of variance explained as a function of the number of clusters.

Second, the study was conducted with near-experts at one point in time. For that reason, it is unclear whether the number of clusters and the distribution of the trials of one athlete to the different clusters are the same for top experts or novices and how the distribution to the different clusters change over time. One might assume that training leads to a change of the distribution of the movement execution to the different clusters. Either the movement patterns become restructured, which would be reflected in a more reliable distribution of different skill executions to one cluster. Or the distribution of the skill executions of one athlete moves to a different cluster, which would be reflected in a less reliable distribution of different skill executions to one cluster.

Third, there should be some effort to study other gymnastic movements and their prototypical movement structures as well as how they appear in the variant and invariant features. This is relevant particularly in gymnastics because of the varying environmental constraints due to the different gymnastic apparatuses. The handspring is not only performed on vault, but it is also part of floor routines. The same fundamental movement has to be carried out in different ways, dependent on the features of the gymnastic apparatuses.

Furthermore, it would be interesting to investigate the relations between movement characteristics and the evaluation of the performance. It should be investigated whether the different prototypes are scored differently and how the movement characteristics, especially their variant and invariant features, find expression in observers' gaze behavior and when judging and evaluating the corresponding prototypes.

The current approach opens up interesting practical applications. With regard to gymnastics training, this study provides further evidence for the demand of individuality in training in terms of an optimal organization of the complex functional movement system to solve the movement task. By an adjustment of the skill execution of one athlete with the different prototypes, the skill level of the athlete could be easily determined and a specific training could be implemented. Depending on the similarity of the skill executions of one athlete to one specific prototype, different instructions in the training process might be beneficial.

CONCLUSION

Overall, the approach utilized in this study allows one to identify structural characteristics of movement patterns of a complex gymnastics skill. Therefore, this approach seems to be an appropriate and promising tool, not only for the analysis of gymnastics skills but also for a wide range of applications in various adjacent areas. The results open up practical applications as well as further fruitful research questions.

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