Original Article

Movement prototypes and their relationship in the performance of a gymnastics floor routine

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ABSTRACT

For a better understanding of complex gymnastics performances, on the one hand, it is relevant to analyse isolated time discrete parameters, but on the other hand, it is also relevant to analyse the time-course of gymnastics skills and sequences holistically. Thus, the purpose of this study was to realize a holistic examination of a gymnastics floor routine (round off, back handspring, backward layout somersault) with an innovative approach of analysing time continuous data using a cluster analysis. Fifty-eight floor routine trials from ten female near-expert gymnasts were analysed on their movement kinematics. Time courses of six joint angles, together with the trunk orientation angle, were analysed by means of a hierarchical cluster analysis. In addition, the coefficients of variation were calculated. The results of this study revealed that for near-expert gymnasts, three to four prototypical movement patterns could be identified for each of the three skills (round off, back handspring, backward layout somersault). The different prototypical movement patterns can be differentiated by certain variant and invariant characteristics, such as the time courses of the different joint angles and their coefficients of variation. Statistically significant relationships were found between prototypes of the different gymnastics skills. In light of the training process in gymnastics, the study provides further evidence for strongly considering gymnasts' movement pattern as well as for focusing on particular movement characteristics rather than on particular gymnastics skills in regard to motor skill acquisition and optimization.

Keywords: Kinematic analysis; Cluster analysis; Prototypical movement patterns; Complex system; Movement relationship.

Cite this article as:
Mack, M., Federbusch, S., Ferber, M., & Heinen, T. (2020). Movement prototypes and their relationship in the performance of a gymnastics floor routine. *Journal of Human Sport and Exercise*, *15*(2), 303-318. doi:https://doi.org/10.14198/jhse.2020.152.06

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Submitted for publication March 2019
Accepted for publication May 2019
Published June 2020 *(in press* June 2019)
JOURNAL OF HUMAN SPORT & EXERCISE ISSN 1988-5202

doi:10.14198/jhse.2020.152.06

INTRODUCTION

Artistic Gymnastics involves very complex and technically challenging sequences of skills requiring maximal effort as well as a high level of functional ability, such as flexibility and coordination (Arkaev & Suchilin, 2004). Therefore, the movement-concerned components are related to each other (Davids et al., 2014). For instance, the movement of the legs in a particular situation might influence the movement of the trunk due to interacting joint torques (Enoka, 2002). Consequently, skills that are performed in sequence also interact with each other. Imagine a gymnast performing a round off with a subsequent back somersault. The performance of the round off (i.e., variation in linear and angular momentum) influences the subsequent somersault (King & Yeadon, 2004). Thus, for a better understanding of gymnastics performance, the time course of the whole sequence of skills should be taken into account rather than collecting individual parameters (Troje, 2002). There are a large number of studies in the field of sports science and gymnastics investigating isolated biomechanical aspects of different gymnastics skills (Prassas, Kwon, & Sands, 2006). However, there is a lack of research concerning the investigation of gymnastics sequences in a holistic way regarding the movement variability within one skill but also relating to how this movement variability influences the relationship within a sequence of skills. Therefore, the goal of this study was to identify different prototypes and their variant and invariant characteristics using an innovative method that allows the analysis of gymnastics skills in a holistic fashion. In a second step, the relationships between those prototypical movements in a sequence of skills were investigated.

Gymnastics skills, similar to other goal-directed activities, can be seen as complex systems. Complex systems are composed of many different variables that interact among themselves and as a whole with the environment. These interactions change depending on the constraints provided by the task, the environment or the gymnast, thus making it impossible to completely pre-program their time-course in advance (Bernstein, 1967; Davids et al., 2014; Higgins, 1977). This, in turn, leads to a particular amount of variability that is reflected in distinguishable movement options that could be described by a specific structure of biomechanical parameters (Latash, Scholz, & Schöner, 2002). Traditionally, movement variability has been treated as an aspect of human behaviour that is not functional (Newell, Deutsch, Sosnoff, & Mayer-Kress, 2006). Currently, through the introduction of nonlinear statistical models in the study of human movement systems, movement variability is considered to occupy a functional role in human motor behaviour (Thompson & Stewart, 2002). It may be proposed that each skill can be defined behaviourally by a unique set of interacting biomechanical properties (Newell, 1985; Newell et al., 2006).

For example, if the gymnastics skill of a somersault is performed by a certain number of gymnasts a certain amount of time, each of these performances is unique and can be described through a particular set of biomechanical properties (Schöllhorn, Chow, Glazier, & Button, 2013). At the same time, however, some performances look more similar than others. This might imply that more similar performances of the same skill exhibit more similar biomechanical properties, and performances that vary significantly might be defined through different biomechanical properties. Furthermore, there might be some biomechanical properties, that exhibit less variability than others. Certain biomechanical properties are left free to vary, and in many cases, such variability could be viewed as a necessary and functional aspect of satisfying the task demands (Handford, 2006).

Biomechanical research has shown that these characteristics are not only descriptive but also functional. For instance, the Tkatchev, a release and grasp skill on the high and uneven bars, provides a good example of the functional role of particular biomechanical properties of a complex skill. For instance, it could be shown that there was a greater angle of release for different versions of the Tkatchev, as the gymnasts extend the hip joint to reach the release angle (Irwin, Manning, & Kerwin, 2011; Kerwin & Irwin, 2010). The modification of the hip joints can be seen as a functional aspect of changing the angle of release. Another functional role of biomechanical properties can be seen by the comparison of experts and novices. It is suggested that by “freezing” movements of joints and body segments, novices create a controlled solution to reduce the complexity of movements (Bernstein, 1967). In a later stage of learning, more joints and body segments are then “freed”. It should be noted that individual constraints of different performers lead to different learning patterns in terms of the changes in performance and the biomechanical properties (Williams, Irwin, Kerwin, & Newell, 2012).

In gymnastics, especially in floor routines, several skills, such as a back handspring and a back somersault, are performed very quickly one after the other. Seeing gymnastics skills as complex systems, several skills performed in a sequence might not only interact among themselves and with the environment but also interact with each other. Furthermore, a specific version of the back handspring should more likely lead to a specific version of the somersault. Individual constraints, such as the degree of expertise or the biomechanical properties, might be the cause of this variability. To perform a somersault after a back handspring, several requirements, such as a certain linear and angular impulse, have to be met during take-off from the floor, which should be prepared by the preceding skills. The question arises as to which biomechanical properties of the preceding skills are important for successful performance and how those biomechanical properties should be assessed.

Currently, a large amount of kinematic and kinetic data is available to describe human action. However, sports scientists usually identify, measure, and interpret selected variables, especially based on time discrete amplitudes of selected variables (Federolf, Tecante, & Benno, 2012; Young & Reinkensmeyer, 2014). The emergence of dynamic systems theory as a viable framework for modelling the sensorimotor system stimulated a change of thinking in the assessment and investigation of human motor performance. For a valid understanding of human motor performance, the relation of the biomechanical properties over the whole time-space continuum should be taken into account(Schöllhorn et al., 2014). As the pattern of the coordination states depends on the internal and external constraints, the time-space characteristics of the movement pattern provide insight into these constraints and the state of the dynamic system not only at specific moments but also in the movement pathway. Joints and body angles seem to be suitable variables to describe time-space characteristics of a gymnastics skill, because, on the one hand, they are continuous kinematic characteristics, while, on the other hand, they can be used to mathematically derive other time discrete variables (Prassas et al., 2003).

Quantitative technique analysis seems inappropriate for explaining the characteristics of the whole skill, but multivariate statistical methods, such as cluster analysis or principal component analysis, may be able to overcome the aforementioned limitation (Davids et al., 2014; Lees, 2002). Both approaches use relative similarities or proximities of variables as a theoretical statistical basis that matches the idea of movement as a unique set of interacting biomechanical properties. A commonly used measure for mathematical comparisons is the Euclidean distance, which represents the mathematical distance between two objects (Bauer & Schöllhorn, 1997; Schöllhorn et al., 2014). Cluster analysis quantitatively sorts these Euclidean distances, thereby aiming to find groups of objects with a high degree of structural similarity to each other, which can be visualized in a tree diagram (Everitt & Dunn, 2001). Given the natural variation of objects in relation to their analysed qualities, the different clusters contain a certain degree of variability (Troje, 2002).

It can be stated that for a better understanding of complex gymnastics performances, it is relevant not only to analyse isolated parameters, but also to analyse gymnastics skills in terms of the interacting biomechanical properties over their whole time-course. Therefore, the goal of this study was to identify different prototypes and their variant and invariant characteristics by means of an innovative method that allows the analysis of gymnastics skills in a holistic fashion. In a second step, the relationships between those prototypical movements in a sequence of skills were investigated.

In the first step, the time-course of gymnasts' joint angles of separate trials of a sequence of three specific gymnastics skills (round off, back handspring, somersault) were mathematically analysed 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 the second step, the relationships between those prototypes were investigated. In the third step, the variant and invariant characteristics were evaluated qualitatively by analysing the time courses of the joint angles in relation to the different prototypes and the different movement phases. Because there are biomechanical properties of movement organization that are more variable than others, it is hypothesized that the prototypes will differ in their variant and invariant characteristics in specific movement phases.

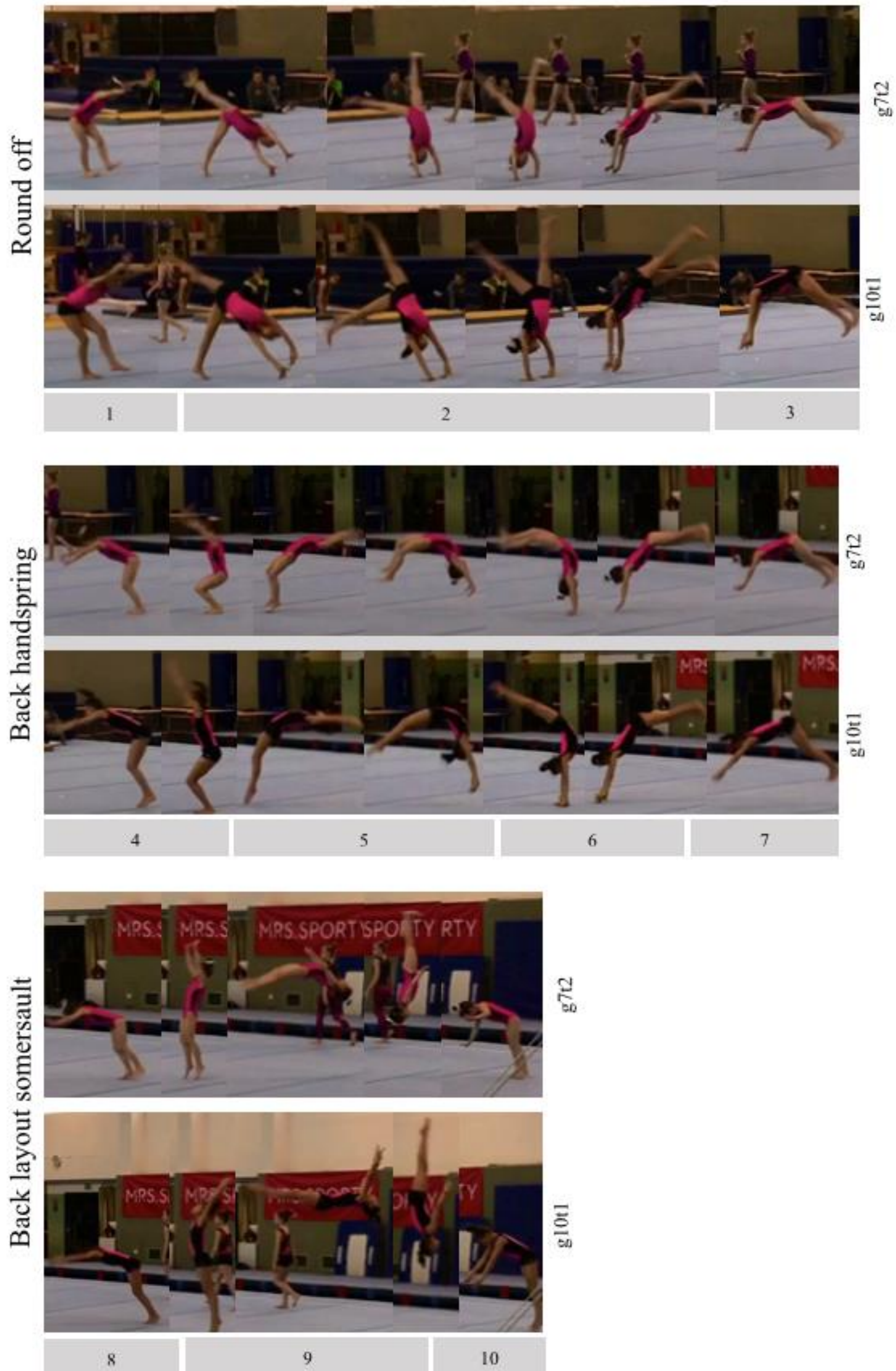
MATERIAL AND METHODS

Participants

Ten female gymnasts (age: M = 11.50 years, SD = 1.43 years) with an average training time of 26 hours per week participated in this study. They were able to perform the experimental task of this study with a high degree of consistency in training and competition (floor routine; see Motor task section). All participants were given oral information concerning the nature and purpose of the study and gave their verbal consent. The gymnastics movements realized for data collection were the same as those performed by the gymnasts during their regular training. The data collection process was nonreactive. There was no manipulation of the participants in the study; they had no time pressure and were wised up about the goal and the procedure of the study. The study was conducted in compliance with the Helsinki Declaration for Human Research and the International Principles governing research on humans and was in line with the ethical guidelines of the local ethics committee.

Motor task

The motor task was a gymnastics sequence on the floor containing the following gymnastics skills: (1) round off, (2) back handspring and (3) back layout somersault. The three skills were performed consecutively on a spring floor that was set up according to the competition guidelines of the International Gymnastics Federation for women's artistic gymnastics (FIG, 2017). Gymnasts were instructed to perform the skills as they would in a regular competition. The moment at which one skill ends and the consecutive skill starts is defined as the point of time when the gymnast touches the floor at the second flight phase to transit to the take-off phase of the consecutive skill. This leads to the following description of the three skills and the corresponding classification of the movement phases of the three skills (Figure 1):



Note: The numbers "1" to "10" correspond to the movement phases of the three skills. The floor routine contains the following prototypes of the particular skills: round off g721 = cluster #2, g10t1 = cluster #1; back handspring g7t2 = cluster #3, g10t1 = cluster #1; backward layout somersault g7t2 = cluster #4, g10t1 = cluster #1.

Figure 1. Illustration of two prototypical trials of the floor routine.

Round off: The round off contains the following movement phases: (1) first flight phase, (2) support phase and (3) second flight phase. It is performed as follows. The round off begins with an initial hop that is performed after a short run-up. The gymnast raises her arms up and forwards. The body rotates forward while the leading leg steps forward, thereby generating initial angular momentum. The leading hand is placed in front of the gymnast on the floor. If the leading hand is the right (left) hand, the second hand is placed further to the right (left) of the centreline, facing backward. The bent leg (right) pushes and the rear leg swings overhead, thereby further translating the initial kinetic energy into whole-body rotation. An accentuated push from the shoulder supports the lift. The turn is made during the hand placement and through the pushing stage from the hands to the feet. By taking a concave shape of the back, the feet touch the floor, and the shoulders rise rapidly with the arms in front of the shoulder (Karacsony & Čuk, 2005; Turoff, 1991).

Back handspring: The back handspring contains the following movement phases: (4) take-off phase, (5) first flight phase, (6) support phase and (7) second flight phase. The skill starts with a jump backward from a standing position. The gymnast moves her arms overhead and extends her hips, thereby engaging an arched body posture. The hands are turned so that the fingers face each other. As the hands contact the mat during the support phase, the elbows may be flexed a bit. Once the body passes over the hands, the legs are snapped down forcefully, while the hands push down hard on the mat. This movement supports taking off from the floor at the end of the support phase. During landing, the body is in a slightly inclined position with the arms in front, and the knees and hips flexed slightly (Karacsony & Čuk, 2005; Turoff, 1991).

Backward layout somersault: The backward layout somersault contains the following movement phases: (8) take-off phase, (9) flight phase and (10) landing phase. This skill usually begins with a take-off position at the end of the back handspring. The arms swing upward and slightly backward with the shoulder being above the feet. The centre of gravity should be on or in front of the gravitational vertical. The hips are pushed forwards and upwards during take-off. During the flight, the body is tightened, and the head is held in a neutral position. The landing is prepared after the shoulders have passed the vertical line. During landing, the knees are slightly bent to absorb the kinetic energy (Karacsony & Čuk, 2005; Turoff, 1991).

Movement analysis

To record the performance of the gymnasts, a digital video camera (240 Hz, 1920 x 1080 pixel) was placed at a distance of approximately 15 meters from the place on the floor where the routine should be performed. Gymnasts' performances were videotaped orthogonal to the movement direction. With the movement analysis system Simi Motion®, the recorded video sequences were digitized for each frame. The digitized horizontal and vertical coordinates of ten points (body landmarks) defined an eight-segment model of the human body (Enoka, 2002). Each body landmark was represented by a two-dimensional time series [xj(t); yj(t)] with j = 1, 2, 3, …, j (t = time, j = frame number). For each video sequence, a software built-in digital filter was applied for data smoothing. The time series of the ten body landmarks were cut into three parts, with each of those parts representing one trial of one particular gymnastics skill of the floor routine. For each trial, the time series of each body landmark was time normalized and rescaled to the interval [0; 1000]. Joint angles of six joints and the trunk orientation angle 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, and shoulder of the left and right body sides), reflecting flexion and extension movements, were calculated with regard to the frontal horizontal body axis (Behnke, 2001).

Procedure

The study was conducted in three phases. In the first phase, the gymnast arrived at the gymnasium. She was instructed about the general procedure of the study and was told that she was taking part in a study on kinematic analysis of a gymnastics floor routine. After the gymnast gave her informed consent, she was given a warm-up period of approximately 20 minutes and one optional familiarization trial. In the second phase, the gymnast performed ten trials of the motor task. There was no time pressure, and she was allowed to take breaks as requested. In the third phase, after completing the ten trials, the gymnast was released into an individual cool-down period.

Data processing and Analysis

For further data processing and analysis, the free statistics software R (R Core Team, 2017) was used. First, the prototypes of the three skills of the gymnastics routine on the floor (round off, back handspring and backward layout somersault) were determined using a hierarchical cluster analysis (Mack, Hennig, & Heinen, 2018). For each time course of joint angles (knee, hip and shoulder of the left and right body sides) and the trunk orientation angle (right and left body sides), Euclidean distances were calculated between each pair of the same skill trials (see equation 1: x and y denote a corresponding joint angle between a pair of two trials of the same gymnastics skill and i denotes a point in the rescaled time interval [0;1000]). An exact identical course of two skills of the same course would have a value of zero, and the more dissimilar two trials were, the larger the resulting value. Therefore, a value of zero would have indicated an exact identical course of two skill trials, whereas the larger the resulting value, the more dissimilar the two trials were.

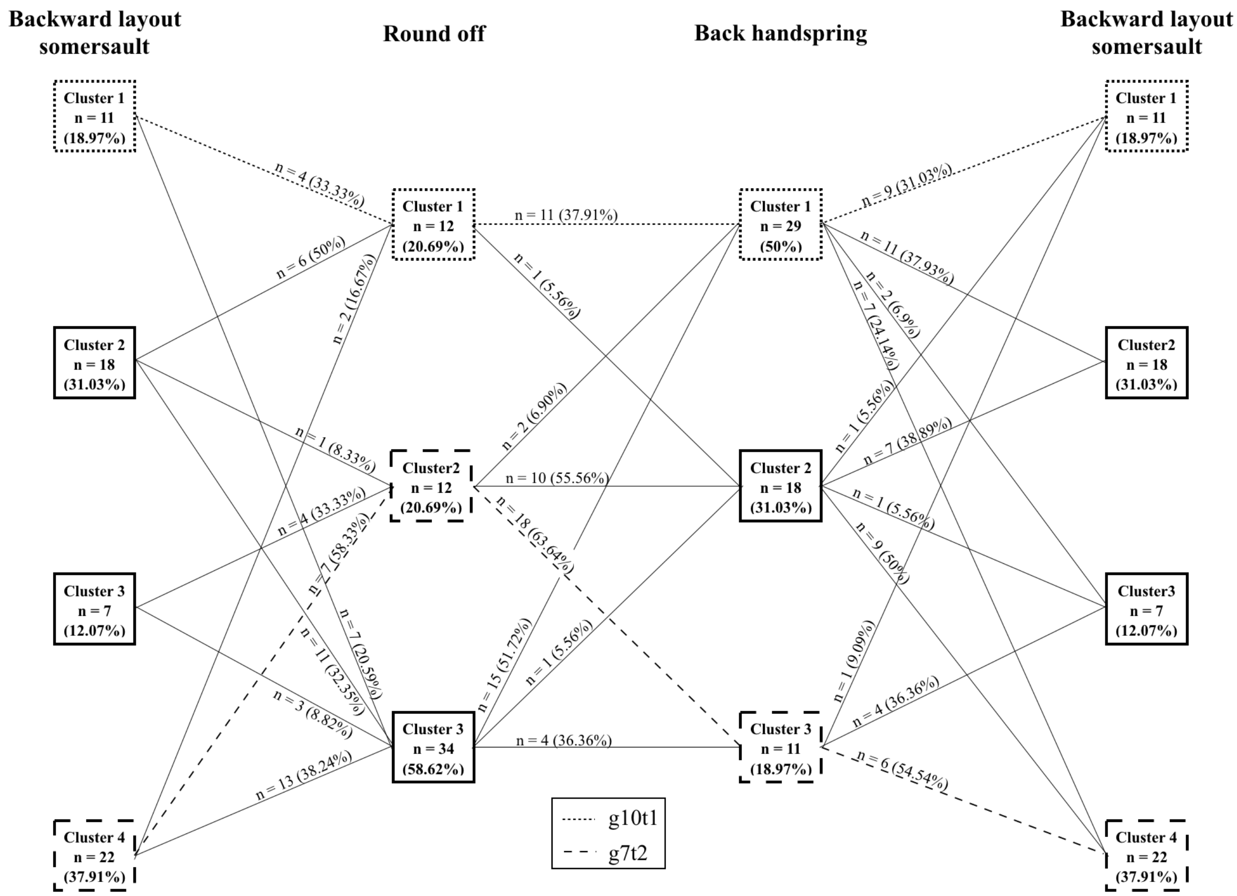
$$d(\mathrm{x,y}) = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2} \qquad \text{Equation 1}$$

A distance matrix resulting from of the calculated Euclidean distance values indicates the similarity between each pair of two trials of the same gymnastics skill. With a hierarchical cluster analysis using Ward's hierarchical clustering method (Ward, 1963), all trials of the same gymnastics skill were evaluated quantitatively by means of their similarity. Ward's method 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 resulting two-dimensional tree-diagram emerged through the fusions or divisions made at each stage of the analysis, illustrating the classification of the trials. The number of clusters was specified by interpreting the scree plot in terms of the elbow criterion (Everitt & Dunn, 2001). In the second step, the relationship between the prototypical movements in a sequence of skills was investigated with Cramer's V correlation method. In the third step, for each cluster, the time courses of the joint angles and the trunk orientation angle were averaged over the corresponding trials to characterize each of the prototypes. To obtain the relative extent of variability of a particular prototype in the passage of time, the time courses of the coefficient of variation were calculated for all joint angles, as well as for the trunk orientation angle of each cluster (Sterigou, 2004).

RESULTS

Structuring of gymnastics skills

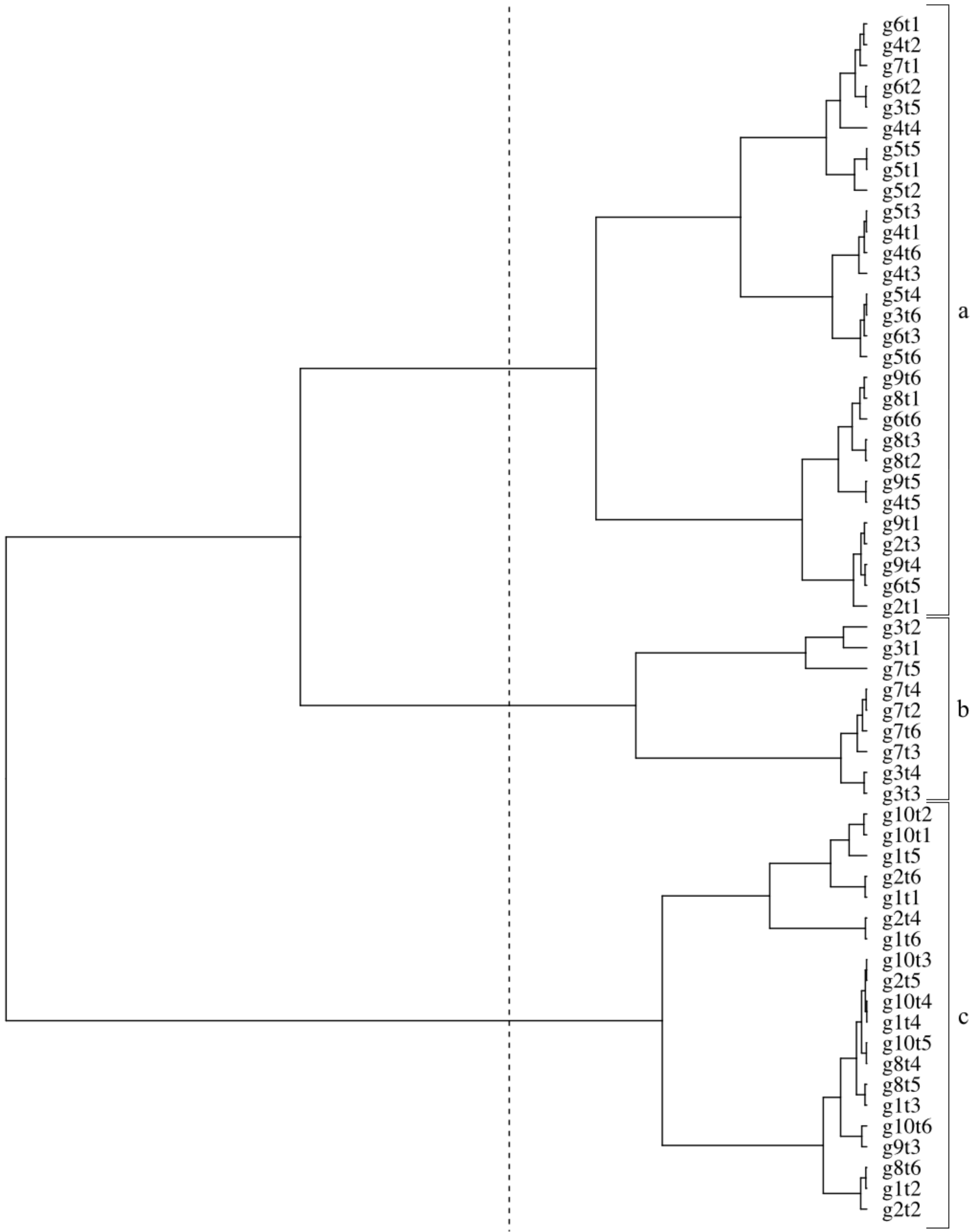
Figure 2 presents the results of the hierarchical cluster for the three gymnastics skills (round off, back handspring, backward layout somersault) performed by the gymnasts. The clusters could be distinguished from each other following the inspection of the scree plot of the cluster analysis. Each of the clusters comprised trials of the respective skill that were more similar to trials within a particular cluster but were more dissimilar to trials in the other clusters. Therefore, each cluster characterized a particular prototype of the respective skill with specific time-space characteristics of the movement.



Note: The lines illustrate the amount and percentage of the trials of a cluster that are related to the following cluster.

Figure 2. Results of the analysis of the relationships between the prototypes / clusters.

Figure 3 presents the resulting tree diagram of the hierarchical cluster analysis for the complete gymnastics sequence on the floor. The hierarchical cluster analyses for the round off, the back handspring and the backward layout somersault revealed similar results with regard to the pattern of the tree diagram.



Note: Horizontal lines indicate the level of the distance at which the respective backward layout somersault trials are grouped into one cluster. The dashed line represents the Euclidean distance below which the clusters are identified. The letters "a)" to "c)" correspond to the three clusters, containing the different prototypical movement patterns of the gymnastics floor routine. g1t1 to g10t6 represent the analysed backward layout somersault trials.

Figure 3. Tree diagram resulting from a cluster analysis using Wards' clustering algorithm.

Relationship between the skill prototypes

To investigate the relationship between the three gymnastics skills in a sequence, Cramer's *V* correlations between the assignments of the trials to the different clusters for the different gymnastics skills were conducted. The assignment of a trial to a specific cluster in terms of the round off significantly correlated with the assignment of a trial to a specific cluster in terms of the back handspring, X^2 (4, N = 58) = 47.986, p < .001, as well as in terms of the somersault backward stretched, X^2 (6, N = 58) = 16.021, p = .014. The assignment of a trial to a specific cluster in terms of the back handspring significantly correlated with the assignment of a trial to a specific cluster in terms of the somersault backward stretched, X2 (4, N = 58) = 18.317, p < .005.

To determine how the assignment of the gymnastics skills in a movement sequence depends on the foregoing skills, the percentage of the trials of a cluster, found again in the different clusters of the following skill, was calculated. The results are presented in Figure 1. Each of the clusters thus comprised trials of the respective movement sequence that were assigned to different clusters in the preceding or following gymnastics skill.

Description of the Prototypes

Each cluster characterized a particular movement prototype within the sample of all analysed movement trials. Some of these clusters were related and some were not. Therefore, a closer look should be taken of the movement characteristics of the clusters of two particular trials (trial 2 of gymnast 7 and trial 1 of gymnast 10) which were assigned to different clusters in the three gymnastics skills. A picture sequence of an exemplary trial can be seen in Figure 1. Exemplary time courses of hip and shoulder joints, as well as their coefficients of variation for the back handsprings, can be found in Figure 4.

Round off

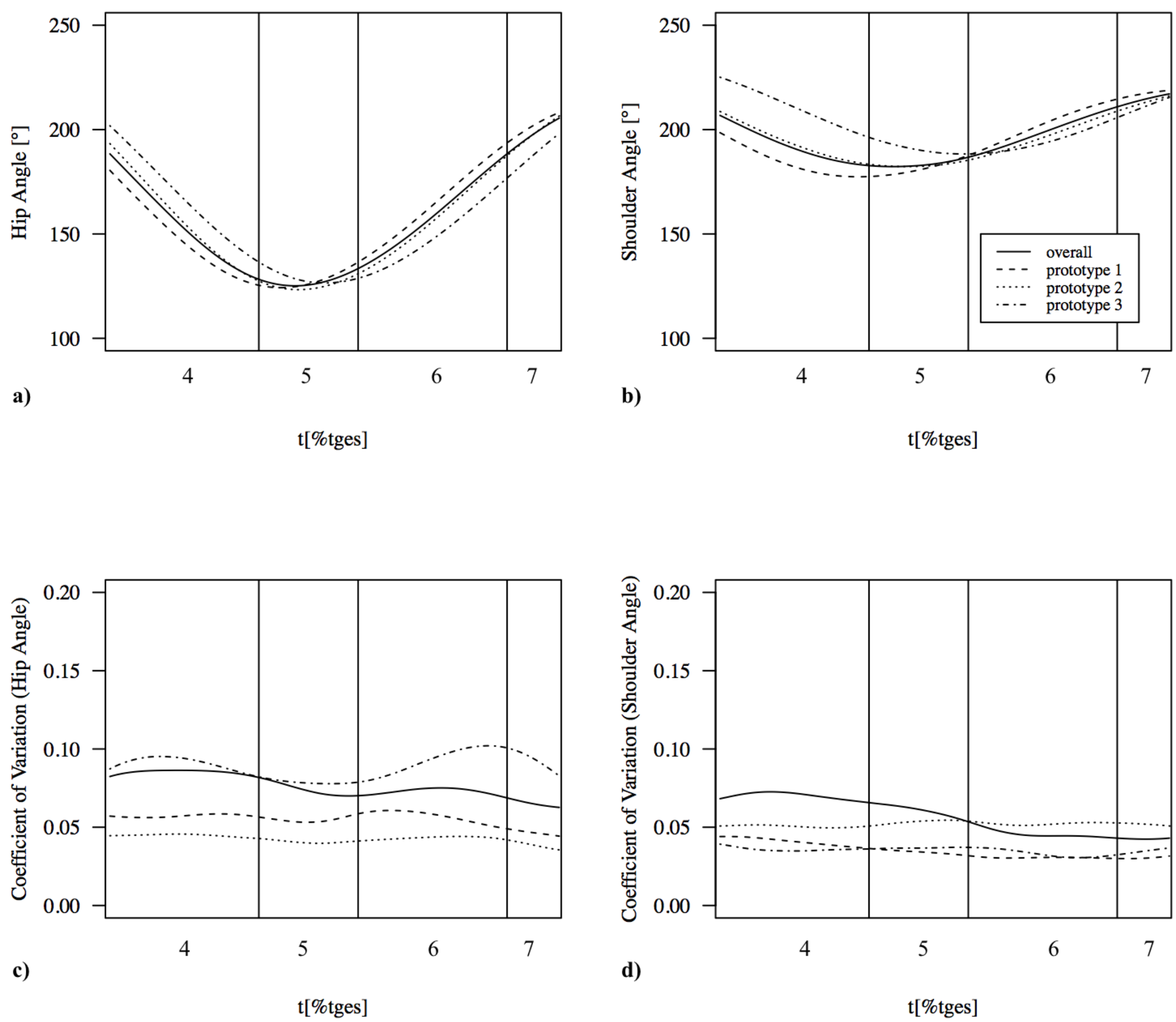
Regarding the round off, trial 2 of gymnast 7 was assigned to cluster #2 and trial 1 of gymnast 10 was assigned to cluster #1. In cluster #2, twelve trials were grouped together. A typical round off trial from cluster #2 comprised the following characteristics: (1) Open shoulder angle and flexed left hip joint as well as open right hip joint during the first flight phase. (2) Stretched elbow and shoulder joints, as well as stretched knee angles, and a stretched back during the support phase. (3) Flexed shoulder and hip joint as well as stretched knee and elbow joints during the second flight phase. There was a rather small coefficient of variation for the right hip and the right shoulder joints over the time course (cv = 0.03 - 0.07), especially at the beginning and the end of the round off.

In cluster #1, twelve trials were grouped together. A typical round off trial from cluster #1 comprised the following characteristics: (1) Open shoulder angle and flexed left hip joint as well as open right hip joint during the flight phase. (2) Slightly flexed elbow and shoulder joints as well as stretched knee angles during the support phase. (3) Flexed shoulder and hip joint as well as stretched knee and elbow joints during the flight phase. There was a rather small coefficient of variation for the right hip and the right shoulder joints over the time course (cv = 0 - 0.1), decreasing to the end of the round off.

Back handspring

Regarding the back handspring, trial 2 of gymnast 7 was assigned to cluster #3 and trial 1 of gymnast 10 was assigned to cluster #1. In cluster #3, eleven trials were grouped together. A typical back handspring trial from cluster #1 comprised the following characteristics: (4) Slightly flexed hip and knee joints during the take-off phase. (5) Overarched back, slightly bent knee and slightly flexed shoulder angle during the first flight phase. (6) Slightly bent knees, an open shoulder angle and a hip angle that starts bending during the support phase. (7) Open shoulder angle and flexed hips during the second flight phase. There was a rather small and steady coefficient of variation of approximately 0.05 for the right shoulder joint over the time course and a coefficient of variation between cv = 0.05 and cv = 0.1 for the right hip joint increasing at the beginning and the end of the back handspring.

In cluster #1, 29 trials were grouped together. A typical back handspring trial from cluster #4 comprised the following characteristics: (4) Slightly flexed hip and knee joints during the take-off phase. (5) Overarched back, slightly stretched knee and open shoulder angle during the first flight phase. (6) Stretched knees, an open shoulder angle and a hip angle that starts bending during the support phase. (7) Open shoulder angle and flexed hips during the second flight phase. There was a rather small and steady coefficient of variation of approximately cv = 0.05 for the right shoulder joint and the right hip joint over the time course.



Note: 4 = take-off phase, 5 = first flight phase, 6 = support phase, 7 = second flight phase.

Figure 4. Illustration of time-normalized angle-time plots for the prototypical courses of the right hip angle (a) and the right shoulder angle (b), as well as time courses of the corresponding coefficients of variation for the different prototypes (c, d) for the back handspring.

Backward layout somersault

Regarding the backward layout somersault, trial 2 of gymnast 7 was assigned to cluster #4 and trial 1 of gymnast 10 was assigned to cluster #1. In cluster #4, eleven trials were grouped together. A typical backward layout somersault trial from cluster #4 comprised the following characteristics: (8) Slightly bent knees, shoulder angle slightly above 90° and a trunk orientation of approximately 45° during the take-off phase; (9) open hip angle, stretched knees and a shoulder angle of approximately 45° during the flight phase, (10) slightly bend knees, slightly closed hips and a shoulder angle of approximately 45° during the landing phase. There was a coefficient of variation between cv = 0.03 and cv = 0.11 for the shoulder joint, decreasing during the flight phase and a coefficient of variation between cv = 0.05 and cv = 0.15 decreasing during the backward layout somersault.

In cluster #1, eleven trials were grouped together. A typical backward layout somersault trial from cluster #1 comprised the following characteristics: (8) Slightly bent knees, shoulder angle slightly above 90° and a trunk orientation of approximately 45° during the landing take-off phase. (9) Open hip angle, an overreached back, stretched knees and a closed shoulder angle during the flight phase; and (10) slightly bent knees, slightly closed hips and a shoulder angle approximately 45° during the landing phase. There was a coefficient of variation between cv = 0.05 and cv = 0.11 for the shoulder joint, decreasing during the flight phase, and a steady coefficient of variation of approximately cv = 0.05 over the time course of the backward layout somersault.

DISCUSSION AND CONCLUSION

For a better understanding of complex gymnastics performances, it is relevant not only to analyse isolated parameters but also to analyse gymnastics skills in terms of the interacting biomechanical properties over their whole time-course. Thus, the purpose of this study was to realize a holistic examination of gymnastics skills with an explorative approach of analysing time continuous data and using the detected classification to exploratively investigate how the particular skills correlated with each other in a sequence of gymnastics skills.

The results of this study revealed that for near-expert gymnasts, three to four prototypical movement patterns could be identified for each of the three skills (round off, back handspring, backward layout somersault) as well as the complete gymnastics floor routine. The 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. There is a statistically significant relationship between some prototypes of the different gymnastics skills.

Concerning the assignments of the trials to the prototypes, it is obvious that the trials from one person are not assigned exhaustively to one specific prototype for all three gymnastics skills. Complex systems such as a round off, a back handspring or a backward layout somersault are composed of many different variables that interact among themselves and as a whole with the environment. These interactions change depending on the constraints provided by the task and the environment or the gymnast her- or himself, and without being previously planned (Bernstein, 1967; Davids et al., 2014; Higgins, 1977). This leads to the variability that is reflected in distinguishable movement options that could be described by a specific structure of biomechanical parameters and might explain why not all trials of one gymnast are assigned to one prototype (Latash et al., 2002).

Comparing the different prototypes of the three gymnastics skills with the judgment criteria of the Code of

Points (FIG, 2017), there are prototypes that might receive high scores, and there are prototypes that might receive deductions and thereby lower scores. According to the Code of Points (FIG, 2017), there are deductions for poor technique regarding the movements of the hips, the shoulders, and the knees. Out of the two exemplary movement sequences, the movement pattern of trial 1 of gymnast 10 might obtain a better overall score for the three gymnastics skills than the movement pattern of trial 2 of gymnast 7. In summary, the differences for the round off were especially in movements of the shoulder and the elbow joints for all movement phases. Trial 1 of gymnast 10 showed more stretched elbow and shoulder joints than trial 2 of gymnast 7. For the back-handspring differences were found especially in the (5) first flight phase and the (6) support phase in terms of more flexed shoulder and knee joints for trial 2 of gymnast 7 than for trial 1 of gymnast 10. For the last skill, the backward layout somersault the trial 1 of gymnast 10 and trial 2 of gymnast 7 differed in terms of a more overreached back and closer shoulder joints for trial 2 of gymnast 7 compared to trial 1 of gymnast 10 in the (9) flight phase.

Looking at the manifestation of the particular movement characteristics, for example, the time-space pattern of the knee, shoulder or hip joints one can see that particular movement characteristics of the different prototypes of one of the three gymnastics skills are found again in the different prototypes of one of the other gymnastics skills. The extended knee and hip angle, as well as the open shoulder angle, are characteristics that maintain the whole floor routine in trial 1 of gymnast 10 and might explain the revealed correlations.

From the perspective of the dynamic system theory, the fact that there are different prototypes that emerge under a different set of constraints leads to some considerations concerning the potential role of the prototypes (i.e., coordination states) in terms of motor learning. It may not be so much a matter of physical preparation that gymnast 7 performs worse than gymnast 10, but it could be more a matter of motor coordination, i.e., exploring degrees of freedom. By “freezing” movements of joints and body segments, novices create a controlled solution to reduce the complexity of movements. In a later stage of learning more joints and body segments are then “freed” (Bernstein, 1967). Through learning, the entire layout of the coordination dynamics changes. The prototypes might reveal the qualitative changes of the movement and may also be the point at which behaviour bifurcates or the gymnasts change their learning phases.

This leads to a further aspect. It is unclear whether the number of the clusters of the different gymnastics skills and the distribution of the trials of one athlete to the different clusters are the same for all skill levels from novices to top experts or how the distribution changes by training. One might assume that training leads to a change in the number of clusters and in the distribution of the trials to the different clusters. This is in line with the results of the functional role of biomechanical properties when comparing experts and novices. It is suggested that by “freezing” movements of joints and body segments, novices create a controlled solution to reduce the complexity of movements. In a later stage of learning more joints and body segments are then explored (Bernstein, 1967). It should be noted that individual constraints of different performers lead to different learning patterns in terms of the changes in performance and biomechanical properties (Williams et al., 2012).

A second aspect is related to the question of finding the optimal point of time to proceed to learn more complex versions of a particular skill, for example, a double somersault instead of a single somersault. The perfect point in time might be related to a particular skill performance, which is similar to a particular prototype.

Those considerations in terms of the current approach open up practical implications. With regard to gymnastics training, it can be stated that individuality in training in terms of an optimal organization of the complex functional movement system is an important factor in learning and improving gymnastics skills. The skill execution of one athlete can be categorized by an adjustment of the performance with the different prototype, and thereby beneficial instructions for the training process can be selected. This study provides further evidence that specific biomechanical properties, for example, an open hip angle, were reflected not only in a single gymnastics movement but also in the different gymnastics movements. For the training process this might imply that it would be useful to focus on the biomechanical property that should be improved and not on the particular gymnastics skills. Furthermore, the approach might be used as a diagnostic tool to ascertain stations in the learning process to start learning and training new skills or more complex versions of a particular skill.

There are limitations of this study, and two specific aspects should be highlighted. First, each of the three gymnastics skills was structured into three to four clusters. One might assume that the trials could also be distributed in more or fewer clusters. However, by distributing the trials into fewer clusters, a high number of structural features might be ignored, and by distributing the trials into more clusters, the description of the movement might not be improved. 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 and by the fact that the gymnasts were near-experts concerning the realized gymnastics skills in the sequence. In further studies, the role of gymnastics expertise or motor learning processes in the number of clusters of the different gymnastics skills and the distribution of the trials of one athlete to the different clusters should be investigated. This might, on the one hand, lead to more specific practical implications in terms of the biomechanical properties that are important for gaining expert performance. On the other hand, this might lead to a better insight about the best point in the training process to learn new skills without training too long for a particular skill and losing the performance level of a particular age group or training for too little time, leading to a missing performance basis.

Furthermore, it would be interesting to investigate whether the different prototypes are scored differently and how the movement characteristic finds expression in the gaze behaviour of the observers when judging and evaluating the corresponding prototypes. For floor routines containing more than one gymnastics skills, it should be examined whether there is a primacy or recency effect, i.e., the first or the last gymnastics skill has the highest influence on the judging behaviour because of its higher likelihood of being remembered. Another interesting point is the questions of whether changing the movement characteristics of the beginning skills in a sequence of movements influences the movement characteristics of the preceding skills.

Overall, the approach utilized in this study allows one to identify structural characteristics of movement patterns not only of a complex skill but also their relations in a sequence of those complex skills. This approach might work well for analysing movement in various adjacent areas and can be easily adjusted to a wide range of applications and research questions. The results open up practical applications as well as further research questions.

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