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Analysis of the Long Jump Technique in the Transition From Approach to Takeoff Based on Time-Continuous Kinematic Data

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There are many studies on the biomechanics of the long jump, but few researchers have investigated how the athlete has to perform the last strides in order to prepare for takeoff. In this investigation, a pattern recognition approach was applied to analyze the movement structure during the last strides of the approach run and the jump. Time-continuous kinematic data of 57 trials (4.45–6.84 m) was analyzed. Cluster analysis identified at coarse level different movement patterns for each flight and support phase. Above these structural differences, individual movement patterns were diagnosed, especially for the jump. Further, the contribution of single variables on the differences of the complex movement patterns was determined by discriminant analysis. Based on the results, conclusions were drawn concerning the long jump and individuality in training. Overall, the applied pattern recognition method allows for the identification of structural changes of movement patterns as well as individual movement styles. This offers a wide range of application in various areas like sports training and rehabilitation.

Key Words: long jump, biomechanics, kinematics, pattern recognition, multivariate analysis, individuality

Key Points:

- Kinematic data of the last three strides and the takeoff in long jump were analyzed using a pattern recognition approach.
- Different movement structures for each flight and support phase as well as highly individual movement patterns within these phases were identified.
- Contribution of single variables to the discrimination between movement patterns of flight and support phases was quantified.
- Concerning long jump training, several conclusions concerning takeoff preparation as well as individuality in training could be drawn.

Introduction

Success in long jump performance mainly depends on the ability of the athlete to transform his horizontal approach velocity into horizontal and vertical takeoff (TO) velocity during the support phase of the jump. Biomechanical analyses indicate that the TO is prepared by a lowering of the center of gravity (CG) during the last strides of the approach run (e.g., 1–4). It was stated by Hay/Nohara, that elite long jumpers lowered their CG during the flight phase of the second-last stride and stayed low until they raised it for the TO during the support phase of the jump itself (5). The same authors observed an increase of the touchdown (TD) distance for the last stride and the jump. Further, a lengthening of the second-last stride has been considered as a corresponding factor for the lowering of the CG (e.g., 4, 6, 7), but there are contradictory findings as well (e.g., 2, 8, 9). While it is a common approach for biomechanical analyses, in all studies mentioned above, time discrete data such as heights or velocities of CG at TO and TD of each stride were analyzed. Therefore, the results can only serve as an indicator of what the athlete has done up to this point in his performance or of what he may be able to do from this point (see 5).

Relatively few investigations deal with the problem of how a long jumper should move his/her body segments to achieve the aspired positions. Relating to the movement technique, a backward sweeping or "active" landing of the supporting leg (that can be characterized by a negative touchdown velocity) has been recommended for the last strides as well as for the jump (10, 11). Koh/Hay (10) also stated in their study that elite long jumpers used a less "active" landing in the last stride than in the two preceding strides. Ramlow/Romanautzky concluded from a single case study that the lowering of the CG during the last stride was supported by the motion of the swinging leg that moved in a lower position than in the preceding strides (12). Those results are mainly based on mathematical simulation, the analysis of discrete parameters, or more qualitative considerations.

More detailed knowledge about the movement processing is available if time continuous data are analyzed. Based on a pattern recognition approach, analyses of the time courses of kinematic and dynamic variables have been useful recently in identifying adaptations of ballistic sports movements following motor learning (13) or changes in the environment (14). Similar procedures were also used to investigate structural differences between slightly varying movements—for example, the long jump TO from various heights (15) or between following phases during a singular running movement (16). As a common result of those and several other studies, highly individual movement styles were stated for high performance level athletes as well as for subjects with quite inferior performances (e.g., students; 16–18).

The purpose of this investigation was to study long jump performance in the last strides of the approach run and the jump based on the analysis of time continuous data. Special interest was on two topics: (a) to identify differences and changes of movement patterns in the transition from approach to TO and (b) to investigate to what extent changes in the complex pattern may be explained by single variables that describe partial motions of body segments.

Methods

Data Acquisition and Preprocessing

Eighteen subjects performed a long jump under competitive conditions. All subjects were students or track and field athletes at the regional level. They were aged from 16 to 29 years and of different genders. Subject performances were recorded with one 16-mm high speed motion camera (Locam) at a sampling of approximately 150 Hz. The camera was placed at the front edge of the TO board. The distance from the midline of the long jump runway was 33.45 m. The camera was panned to record the last three steps of the approach run and the jump. A series of markers placed at carefully measured distances along the far side of the runway served as a basis for determining appropriate linear scales as well as a fixed origin for the coordinate system used in the analysis. Internal timing lights were used to mark the sides of the film. They pulsed at a frequency of 100 Hz and therefore provide a basis for determining appropriate temporal scales.

Each trial taken by every subject was filmed. A minimum of 2 and a maximum of 4 trials of each subjects could be analyzed. In total, 57 trials were included in the analysis. The performance of these long jump trials ranged from 4.45 m to 6.84 m.

Each frame of the recordings was digitized using a 16-mm analysis projector and a Digitizer (Kontron Mop) linked to a personal computer. Two-dimensional coordinates of 21 points were calculated per frame. These points included (a) one fixed point that served to calculate the appropriate conversion factor due to the camera panning, and (b) 20 body markers shown in Figure 1a. The calculated time courses were smoothed with a recursive 2nd-order Butterworth filter (12 Hz).

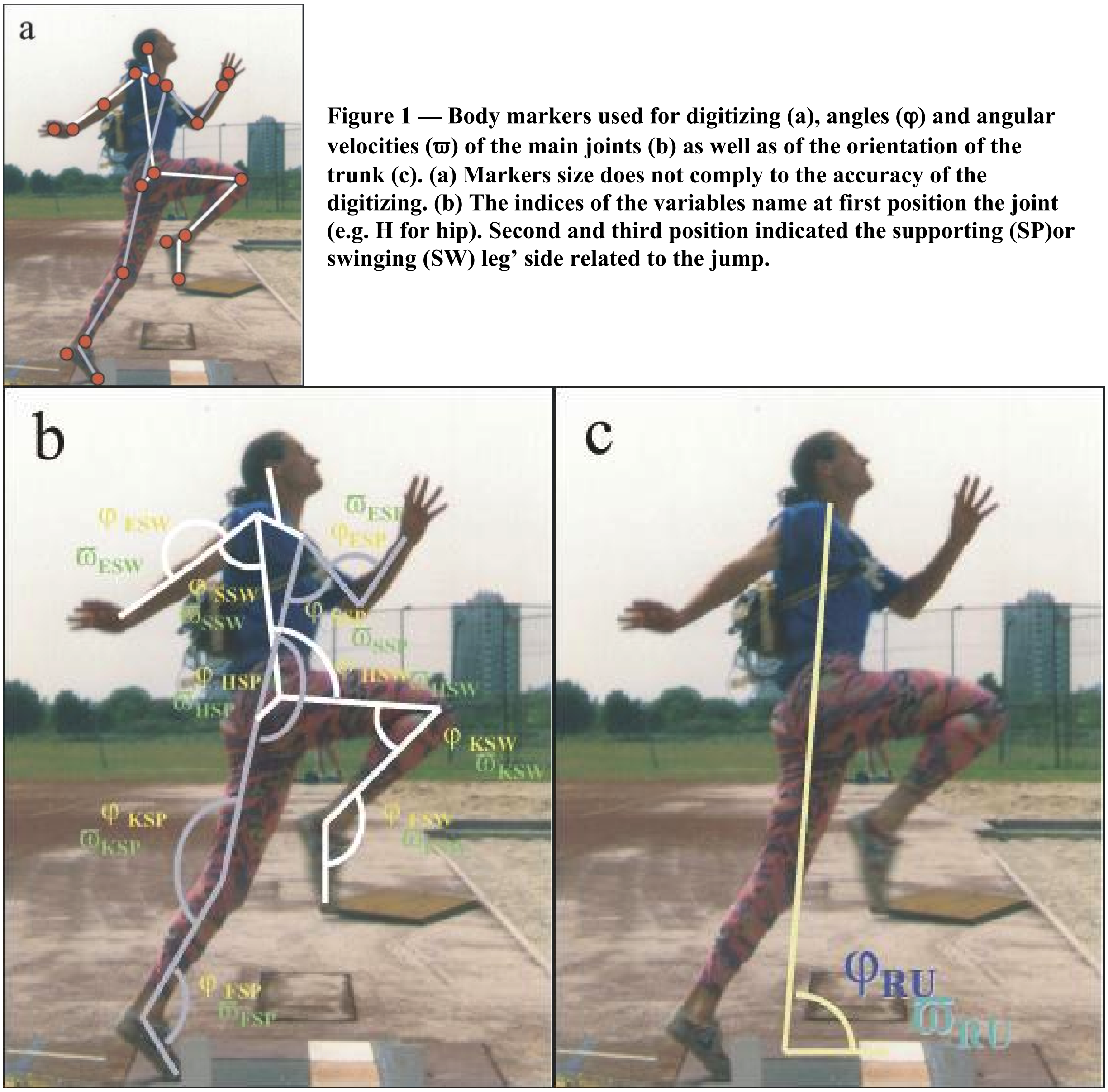

Figure 1 — Body markers used for digitizing (a), angles (φ) and angular velocities (ϖ) of the main joints (b) as well as of the orientation of the trunk (c). (a) Markers size does not comply to the accuracy of the digitizing. (b) The indices of the variables name at first position the joint (e.g. H for hip). Second and third position indicated the supporting (SP)or swinging (SW) leg' side related to the jump.

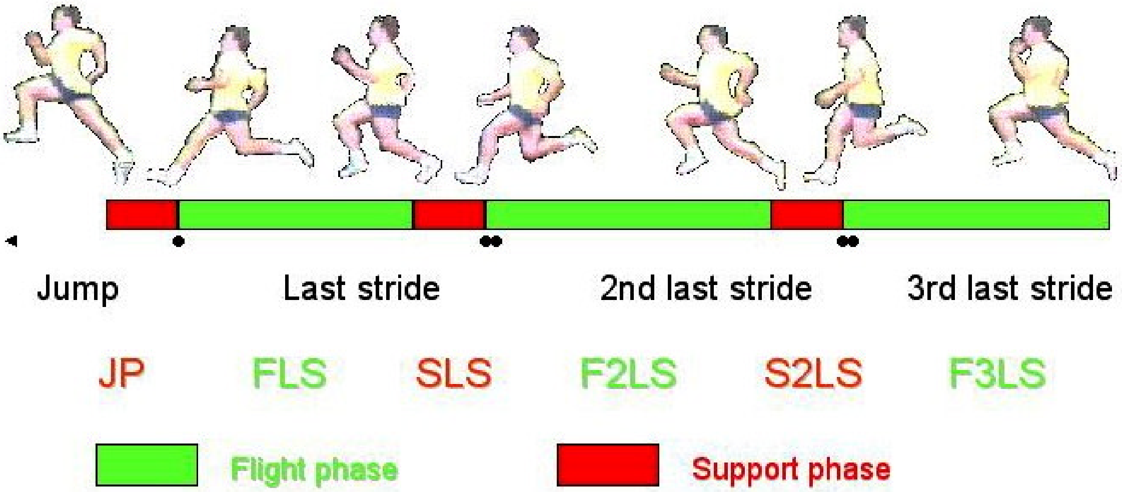

Figure 2 — Support and flight phases of the three last strides of the long jump in relation to the complete performance.

Long Jump Phases and Variables

The long jump can be separated into four phases: approach (including takeoff preparation), takeoff, flight, and landing (5). Long jump performance of the last three stride and the TO were analyzed (Figure 2) because, according to the results of Hay/Nohara (5), at least takeoff preparation and takeoff should be included. Further, each stride was divided into support and flight phases. The support phase started with the first ground contact of the foot at TD and ended with the last contact at TO. The flight phase started with the last contact at TO and ended with the first ground contact of the foot at landing. Altogether, six phases were chosen for the analyses: Flight phases of the third last stride (F3LS), second last stride (F2SL), and last stride (FLS) as well as the support phases of the second last stride (S2SL), last stride (SLS), and takeoff (TO).

To describe the subject's movement during these phases, a 15-segment Hanavan model was used (19), as computed by the coordinates of the 20 digitized body markers. Time courses of angles and angular velocities of the main joints were calculated by the time courses of these markers. In addition, of the orientation angle of the trunk axis and its corresponding velocity, the description was considered physically complete (Figure 1b–c).

Data Processing

The processing of the kinematic data consisted of two major parts: (a) the comparison and classification of complex movement patterns and (b) the determination of the contribution of single variables on the classification. A complex movement pattern was defined as a set of variables (e.g., all angles, all angular velocities, or all variables) that describe the long jump performance over a given time period (e.g., the support phase of the jump). In both parts, data sets of all phases and all trials were compared. While there were 57 trials and six phases per trial, a total of 342 matrices had to be analyzed, each consisting of the time courses of 22 variables. The distances between single variables as well as between groups of variables were determined for all data sets according to Schoellhorn (20; Figure 3, left). The time courses were normalized

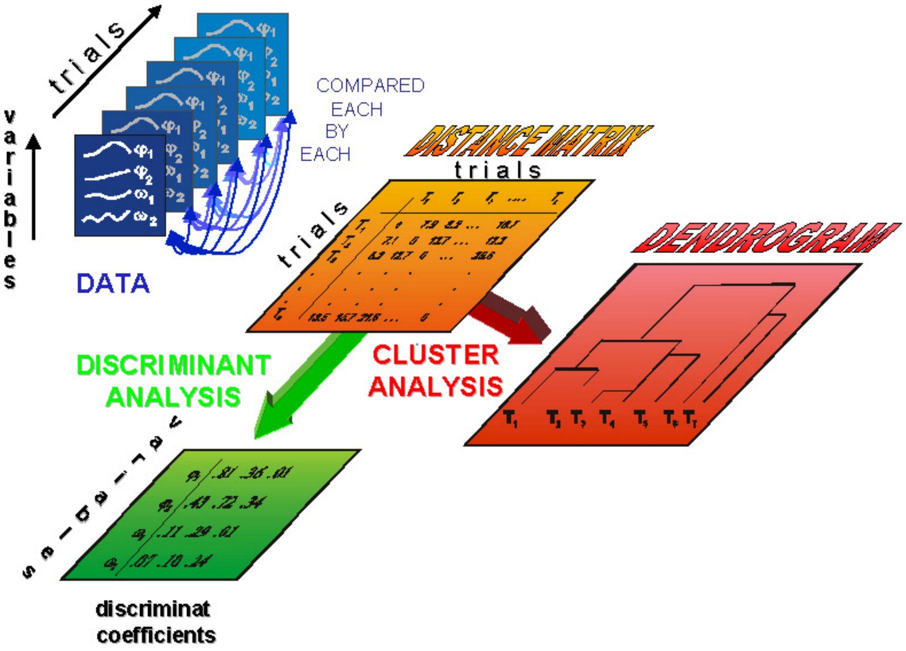

Figure 3 — Schema of process oriented data analysis.

by time and amplitude. For each variable and various sets of variables, distance matrices were formed that contained measures between all phases and all trials.

Classification of Complex Movement Pattern

Distance matrices of various sets of variables were evaluated by cluster analysis using the single linkage algorithm (Figure 3, right). The single linkage algorithm is based on minimizing the distance between two objects; therefore, objects with a small distance are combined at the first steps of the cluster analysis, while objects that share a greater distance are clustered at a subsequent level. Cluster analysis as well as the following multivariate analyses were computed using SPSS (v. 10.0).

In order to obtain a clustering that allows for the differentiation between phases as well as individuals, various distance measures were tested. Cluster analysis showed best results when all variables were included and single Euclidean distances were chosen as distance measure. Finally, an assignment rate of all phases and all athlete trials was determined according to Schoellhorn/Bauer (16; Equation 1).

$$AR = \frac{1}{n}\sum_{i=1}^{n}\frac{m_i}{r_i}$$

Equation 1 — Assignment rate of all phases and all athlete's trials. n = number of subjects, m_i = number of subjects in the largest cluster; r_i = number of trials of one person or phase.

Determining the Effect of Single Variables

Based on the results of the cluster analysis, a discriminant analysis was performed to determine the contribution of single variables on the classification of the complex patterns (Figure 3, bottom). Distance matrices of the single variables were used for the analysis. Each line of each distance matrix was summed up so that, for a single variable, the distance of each object (trial and phase) to all remaining objects was described by one measure. The discriminant analysis was computed using the stepwise procedure. The forward stepwise procedures began by selecting the individual variable, which provides greatest univariate discrimination. The initial variable was then paired with each of the other independent variables one at a time, and the variable that was best able to improve the discriminating power of the function in combination with the first variable was chosen. The third variable and any subsequent variables were selected in a similar manner (21, 22). Variables that do not contribute a sufficient increment to further discrimination were excluded. Mahalanobis D^2 served as criterion for the selection. Standardized discriminant coefficients as well as structure coefficients were used to interpret the results. Discriminant coefficient (or discriminant weights) represent the relative contribution of their associated variable to the discriminant function. Structure coefficients (or discriminant loadings) measure the linear correlation between each independent variable and the discriminant function. They reflect the amount of variance variables share with the discriminant function and can be interpreted like factor loadings in assessing the relative contribution of the variables to the function (22).

Referring to the long jump and considering the results of the cluster analysis, discriminant analysis was applied twice to determine the contribution of single variables on the separation between two phases. Paired phases were the support phases of the second last stride (S2LS) and the jump (JP) as well as the flight phases of the third last stride (F3LS) and the last stride (FLS), respectively.

Results

Considering all angles and angular velocities, the cluster analysis separated at coarse level the flight phase of the second last stride (F2LS) and the support phase of the last stride (SLS) from all other phases (Figure 4). The second step identified all phases, with a recognition rate of 100% for F2LS and the SLS. The recognition rate of the remaining phases was between 77 and 85%. At a more subtle level, personal long jump styles could be assigned for the support phase of the jump (88%) and the SLS (68%). Up to 58% of the flight phases, but only 37.5% of the support phases of the second last stride, were assessed as individually correct (Table 1).

Discriminant analysis was applied to two samples that contained all data sets of the support phases S2LS and JP or of the flight phases F3LS and FLS, respectively.

For the support phases, 93% of the S2LS and 86% of the JP were classified correctly. Six variables were included for the analysis: the elbow angle of the supporting leg side (φ_{ESP}), the angle and the angular velocity of the swinging leg's ankle (φ_{FSW}, ϖ_{FSW}), the orientation angle of the trunk (β_{TR}), the angle of the supporting leg's hip (φ_{HSP}) and the angular velocity of the swinging leg's hip (ϖ_{HSW}). Standardized discrimination coefficients (Table 2) showed highest

Table 1 Individual Assignment of Long Jump Trials Within Each Support and Flight Phase

Variable	Flight phase		Support phase	
Third-to-last stride	F3LS	53%		
Second-to-last stride	F2LS	49%	S2LS	38%
Last stride	FLS	58%	SLS	68%
Jump			JP	88%

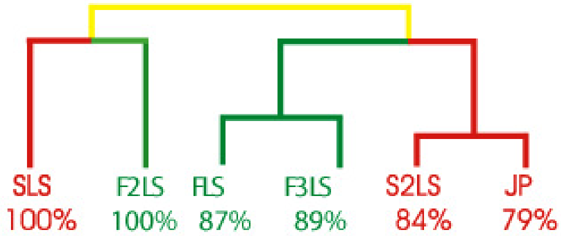

Figure 4 — Results of the cluster analysis for the support phases of the jump (JP), second last (S2LS) and last stride (SLS) as well as for the corresponding flight phases (FLS, F2LS, F3LS). The percental assignment rates are quoted for each phase.

Table 2 Standardized Canonical Coefficients of the Discriminant Function for the Support Phases S2LS and JP

Variable	Coefficient
φ_{ESP}	.651
φ_{FSW}	.559
β_{TR}	.488
ϖ_{FSW}	–.378
φ_{HSP}	.315
ϖ_{HSW}	–.274

Note. Discriminant analysis using the stepwise procedure included six variables. Variables are sorted by the absolute value of the discriminant coefficients.

Table 3 Common Correlation in Between the Support Phases S2LS and JP Between the Discriminant Variables and the Standardized Canonical Discriminant Functions

Variable	Structure coefficients
β_{TR}	.549
φ_{ESP}	.518
φ_{HSP}	.382
φ_{FSW}	.351
ϖ_{HSW}	–.206
ϖ_{FSW}	–.059

Note. Variables are sorted by the absolute value of their correlation coefficients.

values for the variables φ_{ESP} (.651), φ_{FSW} (.559), and β_{TR} (.488). Structure coefficients higher than 0.5 were observed for the variables β_{TR} (.549) and φ_{ESP} (.518; Table 3).

According to the flight phases, discriminant analysis classified 93% of the F3LS and 91.2% of the FLS correctly. As for the analysis of the support phases, six variables were included. Flight phases were discriminated best by the angular velocities of both knees (ϖ_{KSW}, ϖ_{KSP}), of the swinging leg's ankle (ϖ_{FSW}), and of the supporting leg's hip (ϖ_{HSP}) as well as the orientation angle and angular velocity of the trunk (β_{TR}, υ_{TR}). Discriminant coefficients and structure coefficients are displayed in Tables 4 and 5, respectively. Highest values for the discriminant coefficients were obtained by ϖ_{KSW} (.702) and β_{TR} (–.686). The angular velocities of the swinging leg's knee (ϖ_{KSW}) showed the highest value of the structure coefficients (.673).

Table 4 Standardized Canonical Coefficients of the Discriminant Function for the Flight Phases F3LS and FLS

Variable	Coefficients
ϖ_{KSW}	.703
β_{TR}	–.686
ϖ_{FSW}	.402
ϖ_{KSP}	–.362
υ_{TR}	.332
ϖ_{HSP}	.296

Note. Discriminant analysis using the stepwise procedure included six variables. Variables are sorted by the absolute value of the discriminant coefficients.

Table 5 Common Correlation in Between the Flight Phases F3LS and FLS Between the Discriminant Variables and the Standardized Canonical Discriminant Functions

Variable	Structure coefficients
ϖ_{KSW}	.673
β_{TR}	–.421
ϖ_{KSP}	–.310
ϖ_{HSP}	.191
υ_{TR}	.161
ϖ_{FSW}	.038

Note. Variables are sorted by the absolute value of their correlation coefficient.

Discussion

Following the results of the cluster analysis, different movement patterns for support and flight phases of each stride can be diagnosed. Especially long jump performance during the flight phase of the second last stride (F2LS) and the support phase of the last stride (SLS) differs from the performances of the previous as well as the following flight and support phases. This can be explained by the changes of swinging and supporting leg during following steps in long jump approach: The same leg is used for the support of the second last stride and the jump, whereas the last stride is supported by the other leg. Further, structural differences can be observed between support and flight phases. While these results in principal correspond to the findings of Schoellhorn (20) for a cyclic running movement, the assessment rates coincide mainly for the F2LS and the SLS phases. Such as the support and flight phases in running, these two phases were classified with an assessment rate of 100%. For all remaining long jump phases, assessment rates were about 11 to 21% less.

Above the structural differences of the long jump’s phases, there is a strong indication for individual movement patterns, especially during the support phase of the jump (JP). Eighty-eight percent of the support phases of the jump were individually assigned correctly, which means that the personal assessment rates for the long jump’s takeoff are in the range of the values evaluated for the support phases in running (85%; 20). Results are also comparable for the flight phases (running, 50%; long jump, 49–58%). The relatively low assessment rate for the support phases of the S2LS (38%) might be due to adjustments the athletes made in order to place their TO foot close to the front edge of the TO board.

The results of the discriminant analysis are remarkable especially concerning the flight phases. If the criteria of Guadagnoli/Velicier (23) for the stability of component patterns is taken into account for interpretation of discriminant loadings, structure coefficient higher than .4 might be considered. Referring to both discriminant coefficients and structural coefficients, the movement dynamics of the swinging leg (as described by ϖ_{KSW}) as well as the positioning of the trunk (as described by β_{TR}) seem to be most responsible for the differentiation of the complex movement pattern of the F3LS and the FLS phase. The time courses in Figure 5 (top) illustrate the typical movement behavior associated with this variable. In the first part of both flight phases, an increasing negative angular velocity of the knee can be observed, which means that the knee is bent with increasing velocity. During the second part of the flight phase of the third last stride (F3LS), the amount of angular velocity decreases at approximately the same rate as it increased, while during the last flight phase (FLS), it remains at a nearly constant level or with only a slight decrease. If also the time courses of the angle of the trunk (β_{TR}) are examined, a common characteristic can be noticed. While there are not many changes in the trunk position during the F3LS, a backward motion of the trunk with increasing orientation angle is observable in the FLS (Figure 5, bottom).

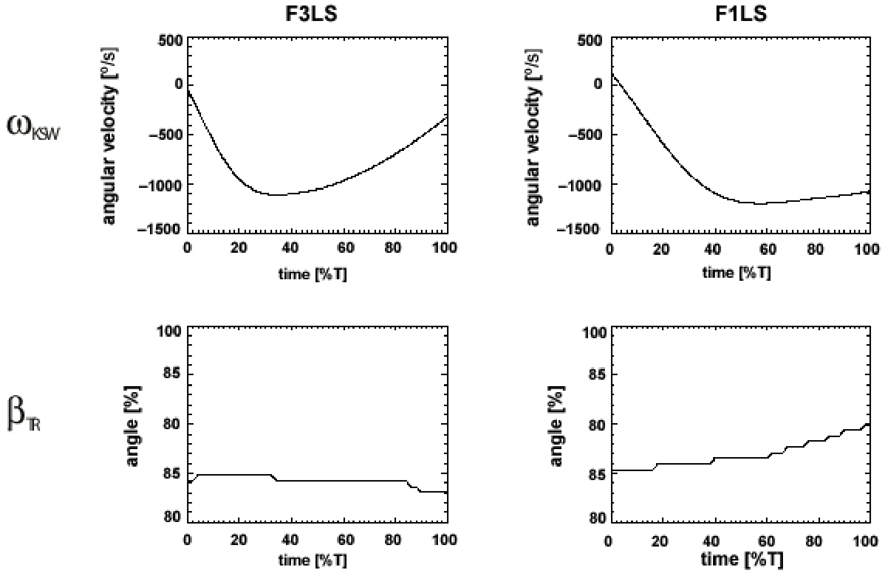

Figure 5 — Time courses of the angular velocities of the swinging leg's knee (top) and of the trunk angle (bottom) for the flight phases F3LS (right) and FLS (left). Curves from the subject DK are displayed as example.

As to the study of Koh/Hay (10), the variables that describe the landing motion of the leg (ϖ_{KSP}, ϖ_{HSP}) differ between both flight phases but do not seem to play a major role for the discrimination.

For the support phases, discriminant coefficients and structural coefficients were lower compared to the flight phases. Time courses of the highest rating variables φ_{ESP} and β_{TR} showed different tendencies for several subjects, which suggests that individual movement styles may cause the discrimination of both support phases.

Conclusions

Overall, the applied pattern recognition method allows one to identify structural changes of movement patterns during a singular movement as well as individual movement styles within the same type of movement. Further, it seems possible to determine the contribution of the motion of body segments on the changes in the complex movement patterns. Therefore, this approach seems to be an appropriate and promising tool, not only for the analysis of sports movements but for a wide range of applications in various adjacent areas like rehabilitation.

Considering the long jump, the movement of the swinging leg, especially its lower part, and the motion of the trunk may play an important role during the preparation for takeoff in the flight phases of the last stride. Certainly, more research is necessary on this point. In particular, there should be some effort to compare support and flight phases across the influence of the changing support leg during the approach run. Complementary, long jump performances of elite athletes should be analyzed.

With regard to long jump training, the study provides further evidence for the demand of individuality in training, which has been postulated in previous studies (24).

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