A Biomechanical Method to Establish a Standard Motion and Identify Critical Motion by Motion Variability : With Examples of High Jump and Sprint Running

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Abstract

This paper proposes a biomechanical method to establish standard motion as the averaged motion pattern of skilled performers and a concept to identify critical technical points using motion variability in examples from the high jump and sprint running. A comparison of the standard motions of takeoff for high jumpers reveals some characteristics of elite male and female high jumpers. Observations of standard motions for male sprinters identifies some characteristics of superior sprinters, such as the appropriate forward lean of the body, large arm swing motion, and the knee and ankle joints of the support leg, which are not fully extended at the toe-off. The coefficient of variation of the distal segments tends to be greater than those of the proximal segments. This suggests that the proximal segments are more important and critical than the distal segments. It is concluded that the method and concept proposed in this study can be applied to create a motion pattern template for good sports techniques so that the standard motion and motion variability can be used to identify the critical points, limiting factors, and technical faults.

Key words: standard motion, motion variability, sports techniques, motion analysis

1. INTRODUCTION

We will first observe the performance and motions of subject athletes and will then compare their techniques and motions with those of superior athletes as the model to improve and optimize those techniques. We will then evaluate and diagnose the subject athletes' techniques and motions and identify technical faults or limiting factors. Finally, we will attempt to teach him or her to modify his or her technique and motion through appropriate training. The essential but most difficult steps in this optimization loop are evaluation and diagnosis of the motion and identification of technical faults and limiting factors.

This process is frequently referred to as technique analysis in sport biomechanics; the concept of technical analysis is less well developed. The methods of technique analysis have been categorized as qualitative, quantitative, and predictive.[10)] Qualitative technique analysis is characterized by observation, evaluation, and diagnosis. The optimization loop of sports techniques mentioned above is representative of a qualitative technique analysis. The other approach to qualitative technique analysis uses a deterministic model of performance, which was proposed by Hay and Reid.[5)] This approach is based on a theoretical model and the result-limiting factor relationships, which are determined by statistical analysis. Their block diagram model has been used to identify performance-related factors in various sports techniques; however, the difficulties of this

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approach are that it does not clarify the desirable motion patterns of sports techniques and it is difficult to apply this approach to some techniques in ball games. Quantitative technique analysis relies on biomechanical data collection to identify key technique variables that affect performance, which are poorly distinguished from other variables that affect performance. A quantitative technique analysis may be ideal for detailed evaluation and diagnosis of some part of a sports technique, but it is time-consuming and may be unsuitable for identifying the characteristics of the overall body motion pattern. A predictive technique analysis based on modeling and computer simulation techniques has great potential for investigating and predicting the ideal motion specific to each athlete. The predictive technique analysis develops and progresses very quickly. However, we have encountered some difficulty in determining the appropriate objective functions and decision criteria to estimate ideal and suitable motions and have not yet reached our goal. While integration and cooperative use of these three approaches would be most effective in teaching and coaching sports techniques, they have not yet been fully developed in the literature and research, much less in the field of teaching and coaching.

It is well known in the teaching and coaching fields that the first step to learning and improving sports techniques is to imitate the motion of superior, skilled performers as a template of model performance. Teachers and coaches frequently adopt a model technique or a template of model performance approach in which sequential pictures and figures of an outstanding athlete or skilled performer are used as the motion pattern model. This approach has some limitations; there may be motion variability even in a model technique that can be attributed to the characteristics of the model athlete, and there is no firm, valid base for determining model technique or ideal form. However, we can overcome these limitations if we prepare some appropriate motion pattern models for sports techniques. The motion pattern model for teaching and coaching sports techniques is not always the ideal model. The average or standard motion pattern is sufficient for practical use.

There is variability in any sequence of human motion. Reduced variability, i.e. consistent repeatability of a motion, is one indicator of a skilled athlete. The motion variability described in the literature[3, 6, 7] is referred to as intra-individual motion variability. Inter-individual motion variability should be the focus in technique analyses, particularly in evaluation and diagnosis of sports techniques, since small motion variability in a given body segment observed among skilled performers indicates that the performers move their body segments in a similar pattern and that the motion pattern that they use is a critical one in that technique. In contrast, substantial motion variability in a segment motion pattern indicates that there are significant variation and personal differences among performers, which can be attributed to the characteristics of the athletes. Therefore, investigating inter-individual motion variability may provide a new approach to evaluation and diagnosis of sports techniques, which are the most important steps in technique analysis.

One attempt to average the motion pattern of superior players was made in a study of the volleyball spike. Hashihara et al.[4] used a three-dimensional direct linear transformation method to average the three-dimensional coordinates of the body segment endpoints of skilled volleyball players that were engaged in official world-level games. They normalized the three-dimensional coordinates of the segment endpoints by the players' body heights and the times elapsed in the movement phases of the volleyball spike before averaging, using a normalizing and averaging technique.[1, 2] While they revealed the average spike motion pattern and several joint angle changes in a spike and provided valuable information for understanding how skilled volleyball players spike a ball, they did not consider or discuss motion variability, and they could not extend the concept to evaluation and diagnosis of sports techniques.

We reviewed literature on technique analysis and considered the accessibility and applicability of biomechanical data to a qualitative analysis or optimization loop of sports techniques. The concept of a standard motion associated with the concept of motion variability will provide us with a new approach to technique analyses. The objectives of this study were to present a method for establishing standard motion as a motion pattern model based on biomechanical analyses of skilled performers and to propose a concept for identifying critical technical points using motion variability by means of examples from athletics.

2. METHODS

2.1 Establishing the Standard Motion

The procedure to establish the standard motion is divided into three basic steps, as follows.

Step 1: Collect two- and three-dimensional coordinate data of the body segment endpoints of skilled performers during the performance of sports techniques in experiment situations or official competitions using ordinary data acquisition techniques such as cinematography, videography, and an automatic motion data capturing system.

Step 2: Normalize coordinate data relative to a reference point, such as the whole body center of gravity or the suprasternale, by anthropometric variables, i.e. body heights of the performers and the time elapsed during each movement phase (support phase, preparation phase, forward-swing phase).

Step 3: Average the normalized coordinate data. The standard motion in this study is the averaged motion pattern of sports techniques.

These steps can be expressed by the following equations.

ri Œ Ri-

$$\mathbf{r}_i = \mathbf{R}_i - \mathbf{R}_{rp}$$

$$\mathbf{nr}_i = \frac{\mathbf{r}_i}{H}$$

$$\overline{\mathbf{r}_i} = \frac{\sum_{j=1}^{n} \mathbf{nr}_{i,j}}{n}$$

$$\overline{\mathbf{R}_{rp}} = \frac{\sum_{j=1}^{n} \mathbf{R}_{rp,j}}{n}$$

$$\overline{\mathbf{R}_i} = \overline{\mathbf{r}_i} + \overline{\mathbf{R}_{rp}}$$

where $\mathbf{R}_i$ is the coordinate vector of point i normalized to the phase time, rp is the reference point, $\mathbf{nr}_i$ is the vector normalized to body height, $\mathbf{r}_i$ is the mean vector, R_{rp} is the mean vector of the reference point, $\mathbf{R}_i$ is the mean normalized coordinate vector, H is the body height, i is the point number, j is the subject, and n is the number of samples.

There are several calculation techniques for steps 2 and 3. One of them is to normalize and average the position vectors that connect the segment endpoints, which can be referred to as the segment vector technique. This technique has the advantage that the calculated position vectors and the direction cosines that express directional information of the body segments can be used to calculate motion variability, as described later. However, it is often cumbersome to define segment vectors, and investigators may have to modify their computer programs to be motion-by-motion specific. For example, one examiner may intend to establish the standard motion of the whole body running, while another may be examining the standard motion of baseball batting, including the bat and ball. For the purposes of this study, we describe the technique to normalize and average coordinate data. This is referred to as a coordinate technique since it is easier to use and apply to various motions than the segment vector technique.

2.2 Calculation of Motion Variability

There are several indicators of motion variability. Ferrario et al.[3] introduced the coefficient of variation (= standard deviation / mean *100; henceforth, *CV*) as an indicator of morphological variation. Winter [11] employed the mean *CV* of an ensemble average normalized to the stride period. However, the *CV* should not be used for variables that include a negative value; a zero division problem arises if it is applied. Hatze [6, 7] proposed the transentrophy function to determine and compare the motion variability of position and velocity. His transentrophy function solved the zero division problem by using a sixth of the maximum range of coordinates and maximum velocities of the segment endpoints as the denominator in his equation instead of the mean in the usual *CV* equation. However, no researchers used his transentrophy function after his papers were published. This may imply that the transentrophy function was complicated and difficult to use in various types of human motion and that the use of the maximum range or velocity is not always appropriate as a denominator to express the extent of variation. Therefore, we decided to use the CV to express motion pattern variability and segment and joint angles, with a modification to resolve the zero division problem.

The *CV* is calculated by dividing the standard deviation by the mean. Figure 1 presents an example of the mean and standard deviation range of the direction cosine in the x direction and the *CV* of the direction cosine for the thigh of the takeoff leg during a high jump takeoff. Although the direction cosine and standard deviation range changed smoothly and crossed a zero reference, the *CV* suddenly rose at the zero crossing points. This is the result of violating the statistical principle that the *CV* should not be used for variables that include a negative value. However, we frequently encounter variables in sport biomechanics that change between positive and negative values and cross a zero reference, such as the segment angle and velocity. We modified the *CV* equation to calculate the *CV* of the direction cosines of the body segments to solve this problem; we call it the modified *CV* or m *CV*.

$$mCV = \frac{SD}{\sum (DC_i + 2)/N} * 100$$

Here, *SD* is the standard deviation, DC_i is the direction cosine, *N* is the number of samples, and value 2 is the range of direction cosine, i.e. ± 1. It is possible to substitute value 1 for value 2.

Figure 2 illustrates the change in direction cosine and *mCV* of the same data as in Fig. 1. The figure reveals that use of the *mCV* eliminated the acute changes on the *CV* curve and the unrealistic *CV* and is appropriate as an indicator to express motion variability.

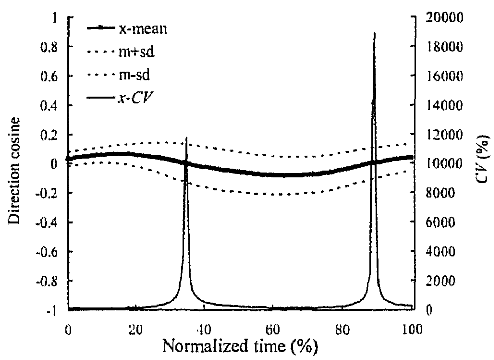

Fig. 1. Change in the direction cosine in the x direction and the coefficient of variation for the thigh of the takeoff leg in a high jump.

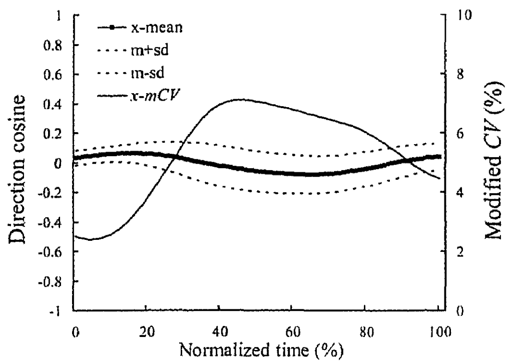

Fig. 2. Changes in the direction cosine and the modified coefficient of variation for the thigh of the takeoff leg in a high jump.

3. RESULTS AND DISCUSSION

3.1 Standard Motion

Figure 3 depicts the standard motion of the high jump takeoff that was established from three-dimensional coordinate data for world-class male and female high jumpers. These data were collected at the 3rd World Championships in Athletics (Tokyo, 1991) using a direct linear transformation technique. A few differences can be observed in the takeoff motions between male and female high jumpers. The male jumpers used a typical double-arm swing in the first half of the takeoff phase, in which both arms are in the back position at the touchdown and then swing downward and upward. The female jumpers used a semi-double arm swing, in which the arm on the opposite side of the takeoff leg is in front of the body

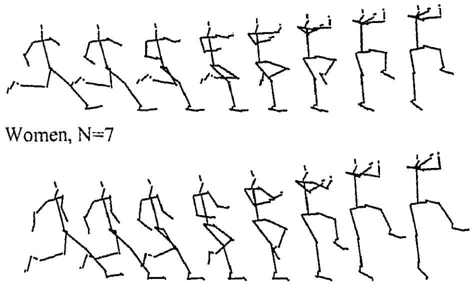

Fig. 3. Standard motions established from coordinate data of elite male and female high jumpers

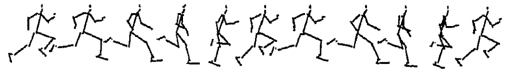

Fig. 4. Standard motions established from coordinate data of elite male sprinters.

at the touchdown. The female jumpers swung their free leg with a deeply flexed knee, while the male jumpers swung their free leg in a more extended manner in the first half of the takeoff. A comparison of the standard motions of the takeoff enabled us to identify some characteristics of elite male and female high jumpers.

Figure 4 shows the standard motion of male sprinters established from seven world-class male sprinters, including Lewis and Burrel (both from the USA) and Fuwa (Japan). We can observe some characteristics of superior sprinters, such as an appropriate forward leaning of the body, large arm swing motion, and the knee and ankle joints of the support leg not being fully extended at the toe-off.[8]

These motion patterns, illustrated by stick figures in Figs. 3 and 4 as examples, appear to resemble our concept of good technique or good form. This indicates that the standard motion can be used as a standard value of a good motion pattern or a template of model performance. In addition, the standard motion can be used to identify characteristic motions for various athlete groups by comparing their techniques with the standard motions, as described for the male and female high jumpers. The validity and reliability of the observation and evaluation processes in an optimization loop or qualitative technique analysis would be diminished without these standard and averaged motions.

3.2 Variability of Motion Pattern and Identifying Critical Technical Points

We recognize that variability exists even in firmly stereotyped motions and that there will be individual differences among skilled performers. Therefore, all the body segment motions that appear in a standard motion are not always complete, firm, and determinate. We examined the standard motions of various sports and some biomechanical variables and found that some body segments and variables exhibited low variability while others varied significantly. Figure 5 depicts the changes in the *CV* of the joint angles during a high jump takeoff. Figure 6 summarizes the variability using the average modified *CV*s of the direction cosines for the body segments and some joint angles during a high jump takeoff. The *CV* of the shoulder joint angle on the side of the free leg in Fig. 5 is greater than the angles of the legs, and the *CV* of the takeoff leg knee is smaller than those of the free leg. It is noteworthy that the *CV*s of the takeoff and trunk in Fig. 6 are smaller that those of the arms and free leg. This implies that the motions of the takeoff leg and trunk tended to be similar among elite male high jumpers, although a simple observation of their performances revealed that the takeoff leg motion differed from jumper to jumper.

Thus, the *CV*s of the distal segments tended to be greater than those of the proximal segments. This may be interpreted to indicate that the proximal segments are more important and critical than the distal segments. It also suggests that coaches and athletes in technique training should pay more attention to the motions of the proximal segments, although they are not easily observed by the naked eye.

3.3 Interpretation of Large Motion Variability

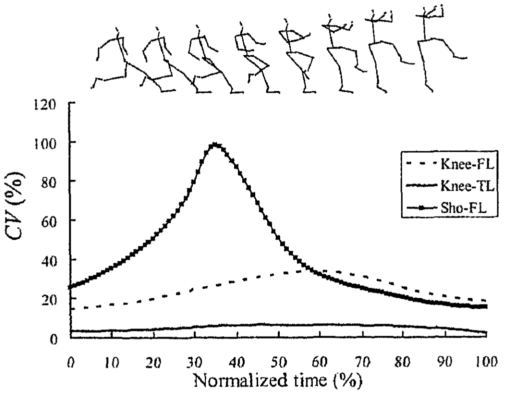

Fig. 5. Changes in coefficients of variation for the joint angles during the takeoff phase of a high jump:(Knee-FL, knee joint of the free leg; Knee-TL, knee joint of the takeoff leg; Sho-FL, Shoulder joint of the free leg side.

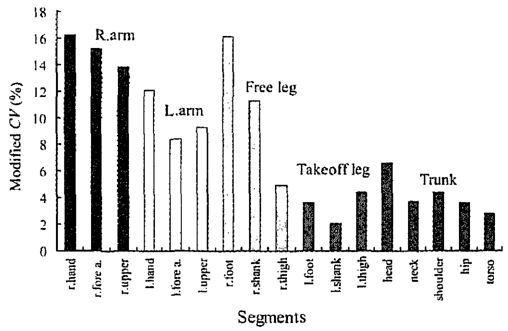

Fig. 6. Average coefficients of variation of the direction cosines for the body segments and the joint angles during a high jump takeoff.

There are two possible interpretations of a large *CV*. A sizeable *CV* may be attributable to some individual differences, and motion variability of segments with a large *CV* may be trivial and tolerable in the technique in question. The other interpretation is that the segments and variables with a substantial *CV* represent limiting segments and factors of the performance under examination. One method to identify which interpretation is more suitable for a specific sports technique is to calculate the correlation coefficients between the variables with a large *CV* and appropriate performance indicators, such as the jumping record, takeoff velocity, and horizontal velocity of the center of gravity during a sprint.

Figures 7 and 8 illustrate changes in the correlation coefficients of segment and joint angles to the performance indicators for the high jump and sprint. We used the vertical velocity of the center of gravity at the toe-off for the high jump and the average horizontal velocity in one running cycle (two steps) as performance indicators. The correlation coefficient in these examples at a significance level of 5% was 0.755. Figures 9 and 10 present schematic summaries of the *CV*s and correlation coefficients of the segment and joint angles to the performance indicators. The knee joint of the free leg and the shoulders for the high jump in Fig. 9 revealed a large *CV* but low correlation coefficients. This indicates that the variability of these joints did not affect the performance very much and that individual differences may be allowable. In contrast, the thigh of the free leg and the ankle of the takeoff leg appear to be important because of their small *CV*. An interesting result was obtained in the foot angle of the support leg in the sprint in Fig. 10, which yielded a large *CV* and high negative correlation coefficient. This indicates that there was a significant difference in foot motion among the elite sprinters and that the faster sprinters tended to not extend their ankle joints as much during the support phase. This finding is partially supported by the results obtained in an investigation of world-class sprinters.[8]

4. CONCLUDING REMARKS

This paper proposed a biomechanical method to establish a standard motion as the average motion pattern of skilled performers and a concept to identify critical technical points using motion variability obtained from examples of high jumps and sprint running. We concluded that the method and concept proposed in this study can be applied to create a motion pattern template for good sports techniques so that standard motions and motion variability can be used to identify critical points, limiting factors, and technical faults.

However, there are some problems and limitations to be resolved in the methods proposed in this study, such as appropriate number of samples required to

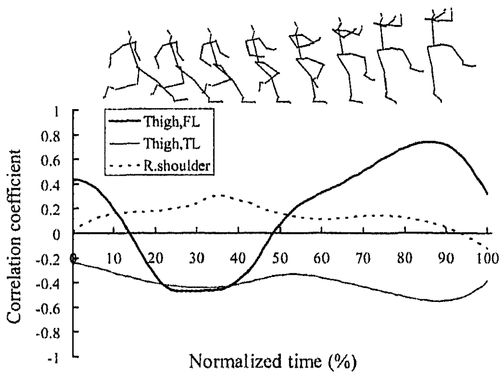

Fig. 7. Changes in correlation coefficients of the thigh angles of the takeoff and free legs and the right shoulder angle opposite the takeoff leg to the vertical velocity of the center of gravity at toe-off in a high jump: FL, the free leg; TL, the takeoff leg; R.shoulder, the right shoulder.

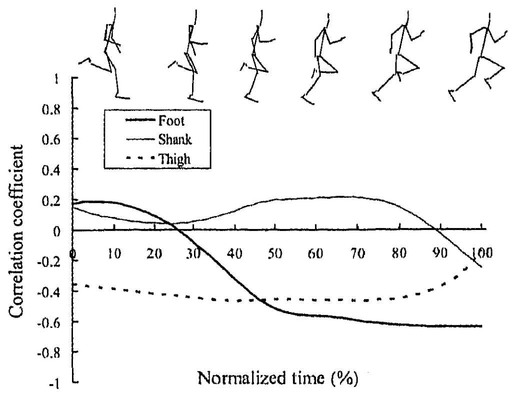

Fig. 8. Changes in correlation coefficients of the segment angles of the support leg to the average horizontal velocity of the center of gravity in one sprint cycle.

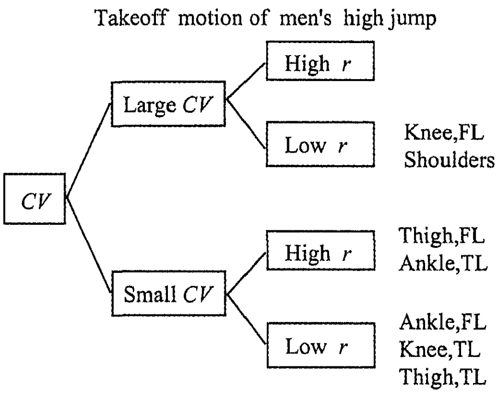

Fig. 9. Schematic summary of the CVs and correlation coefficients(r) of the segment and joint angles to the vertical velocity of the center of gravity at toe-off of a high jump: FL, the free leg,; TL, the takeoff leg; R.shoulder, the right shoulder.

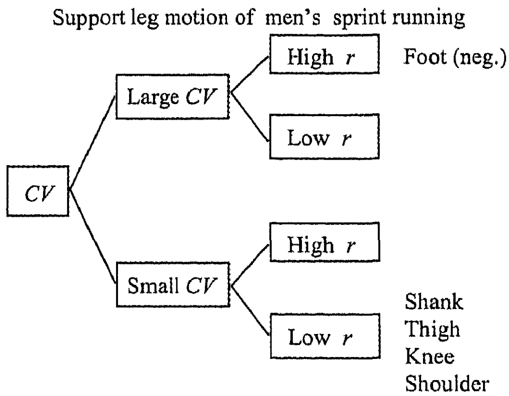

Fig. 10. Schematic summary of the CVs and correlation coefficients(r) of the segment and joint angles to the average horizontal velocity of the center of gravity in one sprint.

establish the standard motion, the levels of performers to be used, how to divide the motion pattern of a sport technique, i.e. into one whole phase or three typical phases (such as preparation, action, and follow-through), and whether the sample used is normally distributed. The normal distribution assumption of samples cannot always be satisfied because of the limitations of the time-consuming and cumbersome data collection process, which may be inherent in any motion capture method. Therefore, use of a nonparametric statistical method to calculate the motion variability is recommended, i.e. the 1st and 3rd percentiles, quartile deviation, and quartile *CV*.[9)]

Future studies into standard motion and motion variability will progress as follows in an attempt to find solutions for the questions cited above.

* The standard motion will be installed in a system for qualitative analysis or an optimization loop of sports techniques as a biomechanical motion database, in which teachers will use various standard motions a comparator or a model for learners and students, depending on their skill levels.
* The system can further contribute to the theory and practice of teaching and coaching, with the help of computer simulation techniques and data feedback technology.
* There should be several sets of standard motions so that various levels of performers can use them to optimize their sports techniques depending on their individual skill levels.
* The standard motion will evolve with an increase in the level of sports techniques of learners and athletes.

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