MANIFESTATIONS OF PROPRIOCEPTION DURING VERTICAL JUMPS TO SPECIFIC HEIGHTS

ARTUR STRUZIK,1 BOGDAN PIETRASZEWSKI,2 ADAM KAWCZYŃSKI,3 SŁAWOMIR WINIARSKI,2 GREGORZ JURAS,4 AND ANDRZEJ ROKITA1

1Departments of Team Games; and 2Biomechanics, University School of Physical Education, Wrocław, Poland; 3Department of Athletes Performance, Faculty of Sport Science, University School of Physical Education, Wrocław, Poland; and 4Department of Human Performance, University School of Physical Education, Katowice, Poland

ABSTRACT

Artur, S, Bogdan, P, Kawczyński, A, Winiarski, S, Grzegorz, J, and Andrzej, R. Manifestations of proprioception during vertical jumps to specific heights. J Strength Cond Res 31(6): 1694–1701, 2017—Jumping and proprioception are important abilities in many sports. The efficiency of the proprioceptive system is indirectly related to jumps performed at specified heights. Therefore, this study recorded the ability of young athletes who play team sports to jump to a specific height compared with their maximum ability. A total of 154 male (age: 14.8 ± 0.9 years, body height: 181.8 ± 8.9 cm, body weight: 69.8 ± 11.8 kg, training experience: 3.8 ± 1.7 years) and 151 female (age: 14.1 ± 0.8 years, body height: 170.5 ± 6.5 cm, body weight: 60.3 ± 9.4 kg, training experience: 3.7 ± 1.4 years) team games players were recruited for this study. Each participant performed 2 countermovement jumps with arm swing to 25, 50, 75, and 100% of the maximum height. Measurements were performed using a force plate. Jump height and its accuracy with respect to a specified height were calculated. The results revealed no significant differences in jump height and its accuracy to the specified heights between the groups (stratified by age, sex, and sport). Individuals with a higher jumping accuracy also exhibited greater maximum jump heights. Jumps to 25% of the maximum height were approximately 2 times higher than the target height. The decreased jump accuracy to a specific height when attempting to jump to lower heights should be reduced with training, particularly among athletes who play team sports. These findings provide useful information regarding the proprioceptive system for team sport coaches and may shape guidelines for training routines by working with submaximal loads.

KEY WORDS countermovement jump, motor control, submaximal jump, young athletes

INTRODUCTION

Jumping is an important ability in many sports. In team sports, the level of jumping ability indirectly determines the team’s final success during competition (6,18,33). For example, in volleyball, the skill of blocking, in which a player or players jump to a specific or maximal height and extend their upper limbs above and over the net (without touching the net) to block an attack (spike) by the opponent, is crucial to team success (9,25). In basketball, the 2-legged jump shot has become more frequent, accounting for more than 70% of all shots during a game (31). Therefore, within 20 years the number of jumps during a basketball game increased twofold (29,36). Each sport that involves jumping is characterized by sport-specific jump types. For instance, basketball players and volleyball players perform different types of jumping movements (3).

Jumping abilities are required for both offensive and defensive activities. During attack, basketball players use jumping during jump shots, layups, and dunking. Jumps help to avoid the defensive players and improve scoring chances. Defensive players jump to steal or block the ball, prevent opponents from shooting and passing, and limit the visibility range of offensive players. Similar jumps are observed during handball games. In addition, in basketball, players on both teams fight for the ball in the air near the backboard after a missed shot. In volleyball, jumping is used during blocking, spiking, and serving. Setters also often perform jumps while setting (3,6,18,24). Other actions that involve jumps but cannot be categorized into the above groups should also be considered. In all of these activities athletes often aim to jump to a specific height rather than to the maximum height, although the target height is often near the maximum. Connected, repeated jumps must also be performed at specific heights (to steal the ball or maintain possession), which often leads to performing a maximum height jump (29). Thus, the height of a jump depends strongly on the temporary situation on the court.
In general, jumping ability is related to the properties of the neuromuscular system, which is responsible for proper muscle coordination during jumping (39). An external manifestation of the efficiency of the central nervous system is the quality of the movements performed. Proprioception is based on an accurate perception of forces (muscle tension), timing (movement velocity), and space (position of body segments with respect to each other) during the performance of a particular motor activity. Proprioception is essential to properly use the control impulses (based on the incoming information and evaluation and adequate processing of this information) and facilitates the optimal performance of the motor task. Proprioceptors located in the muscles and tendons provide information to the brain about muscle tone. Furthermore, the proprioceptors present in joint capsules are responsible for information about the changes in intraarticular pressure caused by movements. These systems help humans know their current body position (without seeing). Receiving and processing information from proprioceptors are required for proper reflexes, planning and performing movements, regulation of muscular tension cocontraction of antagonistic muscles, and for increased mental activity (especially regarding body position) (14,17). To properly perform a submaximal jump, maximal capabilities must be corrected in terms of movement patterns and muscular tensions. Thus, the proprioceptive system manifests during the performance of jumps to varied heights.

Kai et al. (19) reported a relationship between the vertical jump height and knee joint flexion angle. Furthermore, Vanreunterghem et al. (41) concluded that movement effectiveness (energy cost reduction) is a driving criterion of the submaximal jump performance technique. Lees et al. (22) stated that submaximal jumps seem to stress the ankle and knee muscle as adequately as maximal jumps. However, maximal jumps are achieved through greater engagement of the hip extensor muscles (22). Despite the substantial interest among researchers regarding vertical jumps (because of applications in sports practices), some questions remain unanswered, particularly concerning submaximal jumps (23,26,29). A limited number of studies have analyzed jumps to a specific percentage height (19,40,41), especially at low heights (25 or 50% of the maximum height). Because of the specific nature of team sports, the proprioceptive system manifests indirectly during the performance of jumps to varied heights. In many team sport games, success requires accurate and well-controlled jumping. Therefore, the efficiency of the proprioceptive system among individuals who play team sports that require jumping to a specific height, such as basketball, volleyball, and handball, is an interesting topic.

A limited number of studies have analyzed jumping accuracy ability. If jumping ability is influenced by different training protocols, we assume that athletes from different disciplines and of different ages and sexes will also be characterized by different jumping abilities (10,27,28,33). Therefore, we evaluated differences in accuracy in the performance of a vertical jump to a specific height among players from different team sports and of different ages and sexes. We also examined whether the level of maximal jumping ability correlated with the accuracy of performing a vertical jump to a specific height. Because jumps are complex movements and are related to the properties of the neuromuscular system, they should include all 3 components of the proprioception system: force, timing, and space. However, to perform a jump to a specific height, adequate force value (muscle tension) must be generated. Therefore, the question is whether the accuracy of a jump to a specific height is related to maximal value of force during the take-off phase. The aim of the present study was to determine the level of ability to control jump height with respect to maximum jumping ability among a group of young athletes in team sport games in which jumping plays an important role.

Materials and Methods

Experimental Approach to the Problem

Proprioceptive system efficiency was evaluated indirectly in young athletes who played team sports and was estimated based on the ability to control vertical jump height. To properly perform a submaximal jump, maximal capabilities must be corrected in the neuromuscular system. Thus, the proprioceptive system manifests during the performance of jumps to specified heights. The dependent variable was the accuracy of performing a jump to a specific height. The independent variables were age, sex, sport discipline, maximal countermovement jump (CMJ) height, and maximum take-off force. In total, 12 teams were studied at the end of a preparation macrocycle.

Subjects

The examinations of selected teams members were performed in a group of 305 participants (age range = 12–16) selected among young individuals who trained at team sport games (basketball, volleyball, and handball). The selected members were the most talented players chosen by coaches for regional teams. A detailed characterization of the study groups is presented in Table 1. Before the tests, each participant was familiarized with the task. Parents were informed about the purpose of the study and provided written permission for the tests. The experiments were performed in the Biomechanical Analysis Laboratory (with PN-EN ISO 9001:2009 certification). The research project was approved by the Senate’s Research Bioethics Commission, and the procedures complied with the Declaration of Helsinki regarding human experimentation.

Procedures

Participants performed a 15-minute warm-up before performing the jumping tasks: 5 minutes of jogging, 5 minutes of dynamic stretching exercises, and 5 minutes of general and...
Jump to Specific Heights

| Table 1. Characteristics of the research groups (mean ± SD).* |
|-----------------------------------------------|
| Group  | N   | Age (y) | Body height (cm) | Body mass (kg) | Training experience (mo) |
|--------|-----|---------|------------------|----------------|--------------------------|
| BMY    | 28  | 13.5 ± 0.5 | 177.5 ± 12.5   | 64.3 ± 12.6    | 40.9 ± 14.2   |
| BMJ    | 14  | 15.1 ± 0.3 | 183.3 ± 12.7   | 72.5 ± 10.2    | 67.4 ± 27.4   |
| BFY    | 26  | 13.6 ± 0.7 | 166.6 ± 9.1    | 53.5 ± 8.2     | 42.6 ± 15.8   |
| BFJ    | 23  | 14.9 ± 0.5 | 171.3 ± 6.2    | 61.0 ± 7.7     | 51.9 ± 19.4   |
| VMY    | 24  | 14.1 ± 0.3 | 175.9 ± 6.5    | 60.9 ± 9.0     | 30.6 ± 17.0   |
| VMJ    | 27  | 15.2 ± 0.4 | 186.3 ± 5.9    | 72.0 ± 7.3     | 32.7 ± 16.0   |
| VFY    | 32  | 13.3 ± 0.7 | 173.2 ± 4.9    | 59.5 ± 7.0     | 37.2 ± 14.9   |
| VFJ    | 19  | 14.7 ± 0.5 | 172.8 ± 6.4    | 63.6 ± 8.3     | 49.3 ± 19.6   |
| HMY    | 34  | 15.1 ± 0.3 | 183.0 ± 4.8    | 71.5 ± 7.6     | 53.9 ± 15.2   |
| HMJ    | 27  | 16.0 ± 0.3 | 184.7 ± 6.5    | 77.4 ± 15.2    | 53.8 ± 17.0   |
| HFY    | 29  | 14.1 ± 0.4 | 169.0 ± 4.1    | 62.5 ± 11.7    | 40.8 ± 15.0   |
| HFJ    | 22  | 14.9 ± 0.5 | 170.2 ± 5.7    | 63.2 ± 10.0    | 52.0 ± 13.8   |
| Total  | 305 | 14.5 ± 0.9 | 176.2 ± 9.7    | 65.1 ± 11.7    | 45.1 ± 18.9   |

*B = basketball; M = male; Y = youth; J = junior; F = female; V = volleyball; H = handball.

test-specific drills, lower leg drills and technique drills, and easy run outs over 30–60 m. Each participant performed 8 CMJs with arm swing. The jumps were repeated 2 times to the following heights: maximum height (hmax), 25% hmax, 50% hmax, and 75% hmax. The 2 maximal height jumps were performed first. Then, the participants were given the following instructions: “Knowing the maximum height you are able to jump to, perform a jump at 25%, 50%, and 75% of your maximum abilities.” During performance of the jump, the subjects were asked not to flex their lower limbs during the flight phase. Whenever a mistake was made during the jump, the jump was repeated. The participant did not receive feedback on the jump height. A maximum CMJ height (based on the mean value of 2 trials for each percentage value) was calculated as a mean of the percentage and the sum of the 2 attempts for the specific percentage value (greater value of the 2 attempts) was recorded. The mean accuracy of the 2 attempts for the specific percentage value ( Dx, for x = 25, 50, or 75) of each jump to a specific height was also calculated. The jump accuracy to a specific height was calculated as a mean of the percentage and the sum of errors methods according to the equations in Struzik et al. (37). We propose equations 1 and 2. The jump accuracy was based on the mean value of 2 trials for each percentage value ( Dx), with the error score calculated both as a percentage (equation 1) and as the total error (equation 2):

\[ D_x, \text{ percentage } = \frac{\sum_{i=1}^{2}[0.01 \cdot x \cdot h_{\text{max}} - h_{x, i}]}{2 \cdot 0.01 \cdot x \cdot h_{\text{max}}} \times 100\%, x \in \{25, 50, 75\}, \] \hfill (1)

\[ D_x, \text{ total error } = \frac{\sum_{i=1}^{2}[0.01 \cdot x \cdot h_{\text{max}} - h_{x, i}]}{2}, \]

\[ x \in \{25, 50, 75\}. \] \hfill (2)

The symbol h_{x, i} denotes successive jumps (i) to a particular percentage height x. The best accuracy result when performing a jump to a specific height was 0, and greater values corresponded to lower accuracy levels. The methodology of the sum of errors yields a quantitative absolute value when exceeding the demanded height, whereas the percentage method additionally normalizes this value with respect to the maximum jump height.

The ground reaction forces during jumping were recorded with an ACCUPOWER force plate manufactured by AMTI (Watertown, MA, USA) with ACCUPOWER software. This equipment enabled an accurate measurement of the take-off and landing time (using the force plate) and aided the assessment of the duration of the flight phase and, consequently, the jump height. Furthermore, the value of the maximum take-off force (F_{max}) during all types of jumps was also recorded. The sampling frequency for the signal from the plate was set at 240 Hz. The jump height (h) was calculated using the following formula:

\[ h = \frac{1}{8}g \cdot t^2 \] \hfill (3)

where t was the flight time and g was the acceleration due to gravity (5,7,12).

In the reliability part, the subjects performed 4 jumps at each percentage of jump (25, 50, 75, and 100%) on 2 consecutive days. During each session, jumps were separated by a 3-minute rest period to avoid fatigue (34).

**Statistical Analyses**

The normality of the distributions of each variable was tested using the Shapiro-Wilk and Lilliefors tests. The data did not follow normal distributions. Thus, Spearman’s rank correlation coefficients were used to analyze the relationships between the maximum jump height and accuracy of performing jumps to specific heights. Differences between variables (stratified according to age categories, sex, and
**Table 2.** Mean values (±SD) of the maximum countermovement jump (CMJ) height \(h_{\text{max}}\) and jump accuracy to a specific height \(D_s\) for each subgroup.*

| Group | \(h_{\text{max}}\) (cm) | \(D_{25}\) | \(D_{50}\) | \(D_{75}\) | \(D_{25}\) | \(D_{50}\) | \(D_{75}\) |
|-------|----------------|----------|----------|----------|----------|----------|----------|
| BMY   | 41.0 ± 7.6 | 70.3 ± 33.4† | 32.5 ± 15.6†† | 10.0 ± 6.1†† | 7.0 ± 3.1 | 6.4 ± 2.9§ | 3.1 ± 2.0§ |
| BMJ   | 45.6 ± 4.4 | 106.8 ± 57.7†† | 39.7 ± 20.7†† | 14.6 ± 9.5†† | 11.9 ± 6.2§ | 8.9 ± 4.5§ | 5.0 ± 3.2§ |
| BFY   | 33.3 ± 3.8 | 106.1 ± 53.0†† | 41.7 ± 22.4†† | 11.0 ± 8.4†† | 8.7 ± 4.4§ | 6.7 ± 3.3§ | 2.7 ± 2.1§ |
| BFJ   | 34.3 ± 5.9 | 92.7 ± 48.6†† | 39.9 ± 19.5†† | 14.0 ± 8.1†† | 7.6 ± 3.4 | 6.6 ± 3.1§ | 3.6 ± 2.2§ |
| VMY   | 42.3 ± 6.2 | 107.4 ± 59.3†† | 38.4 ± 25.3†† | 13.6 ± 9.3†† | 10.8 ± 5.3§ | 7.8 ± 4.7§ | 4.2 ± 2.7§ |
| VMJ   | 47.0 ± 4.7 | 109.5 ± 56.2†† | 45.6 ± 20.4†† | 13.1 ± 11.0†† | 12.9 ± 6.8 | 10.6 ± 4.5§ | 4.5 ± 3.4§ |
| VFY   | 33.0 ± 4.6 | 126.1 ± 60.3†† | 41.6 ± 21.3†† | 10.8 ± 7.0†† | 10.2 ± 4.8§ | 6.6 ± 3.0§ | 2.6 ± 1.7§ |
| VFJ   | 34.2 ± 4.1 | 93.3 ± 44.4†† | 30.0 ± 23.4†† | 9.0 ± 6.8†† | 7.8 ± 3.4§ | 5.0 ± 3.6§ | 2.3 ± 1.5§ |
| HMY   | 42.0 ± 5.5 | 109.7 ± 56.3†† | 47.6 ± 18.0†† | 13.0 ± 7.3†† | 11.3 ± 5.6§ | 9.8 ± 3.7§ | 3.9 ± 2.0§ |
| HMJ   | 45.7 ± 6.7 | 80.1 ± 41.6†† | 32.2 ± 17.2†† | 11.1 ± 6.8†† | 8.8 ± 4.2§ | 7.1 ± 3.6§ | 3.9 ± 2.6§ |
| HFY   | 33.8 ± 6.7 | 117.3 ± 42.4†† | 41.7 ± 15.6†† | 8.9 ± 5.0†† | 9.8 ± 3.7§ | 7.0 ± 2.8§ | 2.2 ± 1.3§ |
| HFF   | 39.0 ± 7.2 | 94.5 ± 57.5†† | 35.2 ± 16.5†† | 8.6 ± 5.4†† | 9.0 ± 5.1§ | 7.1 ± 3.9§ | 2.5 ± 1.8§ |

*B = basketball; M = male; Y = youth; J = junior; F = female; V = volleyball; H = handball.
†Significant differences between variables at \(p < 0.001\).
‡Significant differences between variables at \(p < 0.01\).
§Significant differences between variables at \(p < 0.05\).

The sport) were analyzed using a multivariate analysis of variance. Significant differences between the jump accuracies to specific heights were verified with the Wilcoxon signed-rank test for dependent variables. The level of significance was set at \(\alpha = 0.05\) in all tests.

The relative and absolute reliability across the reliability session were computed using Intraclass Correlation Coefficient (ICC). The relative reliability was evaluated by calculating a 2-way fixed ICC2,1 (for absolute agreement). Reliability coefficients (i.e., ICC values) were interpreted according to Landis and Koch (21): an ICC between 0.00–0.20 was considered poor, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 substantial, and 0.81–1.00 almost perfect.

**Table 3.** Correlation coefficients between maximum countermovement jump (CMJ) height \(h_{\text{max}}\) and jump accuracy to a specific height \(D_s\).*

| Group: | \(D_{25}\) | \(D_{50}\) | \(D_{75}\) | \(D_{25}\) | \(D_{50}\) | \(D_{75}\) |
|--------|----------|----------|----------|----------|----------|----------|
| BMY    | −0.39†† | −0.46†† | −0.08    | −0.05    | −0.16    | −0.03    |
| BMJ    | −0.41†† | −0.45†† | −0.14    | −0.23    | −0.26    | −0.01    |
| BFY    | −0.30†† | −0.61†† | −0.12    | −0.07    | −0.44†† | 0.09     |
| BFJ    | −0.48†† | −0.37†† | −0.10    | −0.20    | −0.03    | 0.10     |
| VMY    | −0.63†† | −0.45†† | −0.37    | −0.40†† | −0.22    | −0.23    |
| VMJ    | 0.04     | 0.25     | −0.34    | 0.26     | 0.03     | 0.12     |
| VFY    | −0.29    | −0.47†† | −0.27    | 0.03     | −0.20    | 0.04     |
| VFJ    | −0.35    | −0.33    | −0.27    | −0.11    | −0.19    | 0.05     |
| HMY    | −0.30†† | −0.42†† | −0.47†† | −0.03    | −0.06    | −0.23†† |
| HMJ    | −0.54†† | −0.43†† | 0.23     | −0.30    | −0.18    | 0.37     |
| HFJ    | −0.21    | −0.14    | −0.09    | 0.37†† | 0.41†† | 0.20     |
| HFF    | −0.22    | 0.41     | −0.01    | 0.07     | 0.63†† | 0.07     |

*B = basketball; M = male; Y = youth; J = junior; F = female; V = volleyball; H = handball.
†Significant differences at \(p < 0.05\).

Results

The reliability of the performed measurements for jumping to 100% of the maximum height was almost perfect (ICC 0.929, 95%). The reliability of the performed measurements for jumping to 75% of the maximum height was almost perfect (ICC 0.833, 95%). The reliability of the performed measurements for jumping to 50 and 25% of the maximum height were almost perfect (ICC 0.887, 95%) and substantial (ICC 0.730, 95%), respectively. The statistical power was sufficient to detect the described differences. For significant changes (\(p \leq 0.05\)), the partial \(\eta^2\) effect size was found between 0.52 and 0.83.

Copyright © National Strength and Conditioning Association Unauthorized reproduction of this article is prohibited.
Table 2 contains the mean values (±SD) of the maximum CMJ heights and jump accuracies to specific heights. The jump accuracy to a specific height increased as the percentage value expected to be reached increased (Table 2). The exceptions were groups of junior female basketball players, junior male volleyball players, and youth male basketball (BMY) players. In these groups, the difference between $D_{\text{S}}$ and $D_{\text{EO}}$ (calculated using the sum of errors) was not significant. Jumps to 25% of the maximum height were (significantly) approximately 2 times higher than the target values.

Table 3 presents the relationships between the maximum CMJ height and jump accuracy to specific heights. We observed negative relationships between the maximum CMJ height and jump accuracy to specific heights (particularly when using the percentage method). These relationships were significant or insignificant depending on the subgroup (most of the significant relationships were among handball players). However, groups of handball players (handball female youth and handball female junior) demonstrated positive significant relationships between the maximum CMJ height and jump accuracy to a specific height (calculated by means according to the sum of errors method).

No significant differences were observed for maximum CMJ height between groups divided according to age, sex, and sport. Only BMY players and youth male handball (HMY) players demonstrated significant differences in the jump accuracy to a specific height. Basketball players demonstrated greater levels of accuracy for jumps to 25 and 50% of the maximum height (for percentage and sum of errors methods).

Table 4 presents the mean values (±SD) of the maximum take-off force ($F_{\text{max}}$) during countermovement jumps (CMJs).

### Table 4. Mean values (±SD) of the maximum take-off force ($F_{\text{max}}$) during countermovement jumps (CMJs).*

| Group | CMJ for $h_{\text{max}}$ | CMJ for 25% of $h_{\text{max}}$ | CMJ for 50% of $h_{\text{max}}$ | CMJ for 75% of $h_{\text{max}}$ |
|-------|-------------------------|-------------------------------|-------------------------------|-------------------------------|
| BMY   | 1,572.4 ± 523.5         | 1,611.0 ± 388.4               | 1,623.3 ± 373.1               | 1,572.7 ± 375.5              |
| BMJ   | 1,896.0 ± 257.9         | 1,967.8 ± 321.1               | 2,031.4 ± 267.8               | 1,956.1 ± 278.4              |
| BFY   | 1,389.9 ± 272.4         | 1,519.1 ± 243.7               | 1,493.4 ± 245.6               | 1,468.9 ± 291.3              |
| BFJ   | 1,569.7 ± 259.1         | 1,702.7 ± 221.2               | 1,650.6 ± 242.9               | 1,639.4 ± 289.4              |
| VMY   | 1,576.8 ± 401.7         | 1,541.6 ± 214.7               | 1,555.6 ± 282.9               | 1,434.3 ± 212.4              |
| VMJ   | 1,782.1 ± 233.7         | 1,922.9 ± 304.5               | 1,771.5 ± 288.9               | 1,847.9 ± 301.9              |
| VFY   | 1,500.9 ± 310.9         | 1,637.4 ± 335.1               | 1,570.6 ± 236.8               | 1,599.3 ± 297.1              |
| VFJ   | 1,561.4 ± 206.5         | 1,728.2 ± 334.5               | 1,667.2 ± 262.8               | 1,578.1 ± 260.9              |
| HMY   | 1,705.1 ± 440.4         | 1,925.6 ± 493.9               | 2,012.9 ± 329.7               | 1,953.6 ± 306.8              |
| HNJ   | 1,982.8 ± 327.8         | 2,232.5 ± 354.0               | 2,214.5 ± 330.0               | 2,103.7 ± 345.1              |
| HFY   | 1,673.7 ± 395.3         | 1,701.0 ± 333.9               | 1,673.3 ± 264.8               | 1,671.8 ± 261.5              |
| HFJ   | 1,768.9 ± 491.6         | 1,948.0 ± 479.5               | 1,835.9 ± 392.3               | 1,995.8 ± 548.0              |

*B = basketball; M = male; Y = youth; J = junior; F = female; V = volleyball; H = handball.

Correlations were found between the jump accuracy to specific heights (percentage and total errors methods) and maximum take-off force.

**Discussion**

Many motor tasks can be performed at maximal (attempts to achieve the highest possible performance) or submaximal (attempts to achieve a certain level of performance) levels of performance. The central nervous system generates an appropriate set of control signals to all muscles involved during the performance of a motor activity. Performing a motor task at the maximum level can be relatively easy because of the existence of a unique set of control signals yielding maximum performance. These optimal control signals may result from learning a motor task over a longer period of time. Performing a motor task at submaximal capabilities is more difficult because of the presence of many movement patterns (and different sets of control signals) that can be used for these tasks (8,22,40,41).

The neural control of jumping is highly complex, and both feedforward (preprogrammed) and feedback (reflex) mechanisms have to be highly adaptive to ensure balance between achieving maximum performance (power) and the risk of overload injuries (39). A vertical jump is a complex movement characterized by eccentric-concentric muscle work during the countermovement and take-off phases, with different characteristics and purposes of the 2 phases. The total duration of the countermovement and take-off phases (which contribute to jump effectiveness) is approximately 0.5 seconds (38). Thus, the movements performed during both phases are regarded as nearly ballistic. Therefore, during the countermovement or take-off phase, movement modifications (corrections) during that respective phase are impossible unless planned before the movement begins.
Control signals must (to a large extent) be preprogrammed. Consequently, jump control relies heavily on the storage capacity of the central nervous system (17,38,40).

A jump performed to a submaximal height has a slightly different movement pattern compared with the maximum jump. A jump to the maximum height is characterized by a greater range of movement in the joints of the lower limbs to achieve greater kinetic energy in the countermovement phase (4,19). Changes are also observed in the proportions of individual muscle and joint contributions (8,22,41). Less energy is needed when performing a submaximal jump; thus, to reduce energy waste, countermovement and arm swing are reduced (16,23,41).

Therefore, during a submaximal performance, active stretch during the stretch-shortening cycle only created minor benefits for the utilization of elastic energy in muscles (11). Consequently, a decline in the accuracy of performing the movement with a reduction in the jump height seems to be undesirable and may cause fatigue. Young athletes, who jump approximately 2 times higher than necessary during the performance of jumps to 25% of their maximum height, consume (unnecessarily) too much energy (42). Performing a series of tasks with excessive intensity (excessive load) might lead to the premature depletion of energy sources. This situation might lower the subject’s performance during the final phases of the game. It should be noted that during the game, the athlete has to cope with quickly changing situations on the court, time pressure, the defensive actions of opponents, and emotions. These issues might additionally deteriorate sport movement efficiency.

To properly perform a task, submaximal capabilities have to be corrected in terms of movement patterns and muscular tensions. Young athletes tended to increase their accuracy when performing a jump to a specific height when the desired percentage value was increased. Thus, young athletes may lack the ability to work within submaximal loads. Young athletes aged 13–15 do not perform a high number of strength exercises during practice. Therefore, a decline in the accuracy of performing a jump to lower target heights may be because of puberty and the changes that occur during physical development (6,20). According to Lloyd et al. (26), children become more reliant on feedforward mechanisms as they mature. Certain age-related developments in short-latency stretch-reflex responses may influence the neural regulation of the stretch-shortening cycle during submaximal hopping. However, in the study performed by Struzik et al. (37) in postpubertal basketball players, the accuracy of releasing a particular value of static torque by elbow joint extensors decreases as the target values decrease. This finding might suggest that the efficiency of the proprioceptive system is nonuniform and depends on the type of motor activity. The level of proprioceptive (or kinesthetic) sensitivity is highest in the body parts involved in a given sport and higher in athletes compared with untrained people. For example, table tennis players can more accurately reproduce range of movement and pressure force (1,2). Furthermore, Han et al. (15) argue that ankle proprioception scores (an active movement extent discrimination test) have a positive relationship with competition level in soccer. Proprioception also has a crucial role in balance control, and ankle proprioception is the most important aspect of balance (13). Because of the efficiency of the proprioception system, basketball players may organize compensatory behaviors with the joints of their upper limbs, which are used for shooting (35). Because of the lack of relationships between jump accuracy to specific heights (percentage and total errors methods) and maximum take-off force, this variable cannot be used to evaluate the efficiency of the proprioception system. The lack of relationships may be because of the presence of too many variables related to jump height (30).

In this study, the maximum CMJ height was negatively associated with jump accuracy to specific heights (particularly using the percentage method). Therefore, an increase in maximum jump height is also accompanied by increased jump accuracy to a specific height. This relationship, however, was not observed in all subgroups. Thus, its regular presence cannot be unequivocally demonstrated.

The maximum CMJ height and jump accuracy to a specific height did not differ between groups divided according to age, sex, and sport (with one exception). The BMY group demonstrated significantly higher jump accuracies to 25 and 50% of their maximum ability compared with the HMY group. This exception may reflect the greater number of jumps performed in basketball compared with handball games. The level of ability (jumping accuracy) analyzed in this study was relatively constant among the groups divided according to team sport.

One limitation of this study may be the different sizes of the groups. In most cases, the groups contained fewer than 30 people. We realize also that the determination of jump height based on the flight phase duration has some limitations and is not a perfect method. However, the measurement error is relatively small compared with other currently used methods.

**Practical Applications**

Proprioception plays a crucial role in the control of human movement, which is fundamental for exercise and sports. Our study analyzed a component of proprioception related to the ability to reach a specific jump height. Because a vertical jump is a complex movement, its proper performance involves all 3 components of the proprioception system: force, timing, and space. This task involves perceptual and motor abilities and also the sensing and differentiation of the position of individual body parts (pelvis, knee, and ankle positions) while using only a percentage of the maximal muscle contraction. The decreased jump accuracy to a specific height when
Jump to Specific Heights

attempting to jump to lower heights should be reduced with training, particularly among athletes who play team sport games in which success requires accurate and well-controlled jumping. A player who jumps lower might miss the ball, whereas a player who jumps higher might lose time. Impaired proprioception might be associated with functional instability, decreased muscle strength (43), or a history of injury (32). These findings provide useful information regarding the proprioceptive system for team sport coaches and may shape guidelines for training routines involving work with submaximal loads.

CONCLUSIONS

Increasing the target jump height increases the accuracy of reaching the desired height. Jumps to 25% of the maximum height were approximately 2 times higher than the target height, which might reflect a lack of ability to work with submaximal loads. A negative correlation between the maximum CMJ height and accuracy of performing the jump to a specific height was observed (particularly using the percentage method). Individuals who had greater maximum jump heights also exhibited greater accuracy when jumping to a specific height. However, these relationships were not significant in all studied groups (stratified by age, sex, and sport). Significant differences in the jump accuracy to a specific height were found only between groups of youth basketball players and youth handball players. Higher levels of jump accuracy to 25 and 50% of the maximum height were obtained by basketball players. Therefore, there was little difference between the subgroups regarding the jump ability analyzed in this study.

ACKNOWLEDGMENTS

This study was financed with funds obtained from the Polish Ministry of Science and Higher Education within the program “Development of Academic Sport 2013” (Grant number: RSA2 019 52). All authors disclose any financial and personal relationship with other people or organizations that could inappropriately influence their work.

REFERENCES

1. Bankosz, Z and Szumielewicz, P. Proprioceptive ability of fencing and table tennis practitioners. Hum Mov 15: 128–133, 2014.
2. Bankosz, Z. Reproduction of movement range and pressure force of the upper limbs in table tennis players. Trends Sport Sci 22: 25–32, 2015.
3. Battaglia, G, Paoli, A, Bellafiore, M, Bianco, A, and Palma, A. Influence of a sport-specific training background on vertical jumping and throwing performance in young female basketball and volleyball players. J Sports Med Phys Fit 54: 581–587, 2014.
4. Bobbert, MF and van Ingen Schenau, GJ. Coordination in vertical jumping. J Biomech 21: 249–262, 1988.
5. Buckthorpe, M, Morris, J, and Folland, JP. Validity of vertical jump measurement devices. J Sports Sci 30: 63–69, 2012.
6. Buiko, K, Michalski, R, Mazur, J, and Gajewski, J. Jumping abilities in female elite volleyball players: Comparative analysis among age categories. Biol Sport 29: 317–319, 2012.
7. Dias, JA, Pupo, JD, Reis, DC, Borges, L, Santos, SG, Moro, AR, and Borges, NG Jr. Validity of two methods for estimation of vertical jump height. J Strength Cond Res 25: 2034–2039, 2011.
8. Downskaia, N. Control of human limb movements: The leading joint hypothesis and its practical applications. Exerc Sport Sci Rev 38: 201–208, 2010.
9. Eom, HJ, Schutz, RW. Statistical analyses of volleyball team performance. Res Q Exerc Sport 63: 11–18, 1992.
10. Fatourou, IG, Jamurtas, AZ, Leontsini, D, Taxildaris, K, Aggelouis, N, Kostopoulos, N, and Buckenmeyer, P. Evaluation of plyometric exercise training, weight training, and their combination on vertical jumping performance and leg strength. J Strength Cond Res 14: 476–476, 2000.
11. Finni, T, Komi, PV, and Lepola, V. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump. Eur J Appl Physiol 83: 416–426, 2000.
12. Garcia-López, J, Peleteiro, J, Rodríguez-Marroyo, JA, Morante, JC, Herrero, JA, and Villa, JG. The validation of a new method that measures contact and flight times during vertical jump. Int J Sports Med 26: 294–302, 2005.
13. Han, J, Anson, J, Waddington, G, Adams, R, and Liu, Y. The role of ankle proprioception for balance control in relation to sports performance and injury. Biomed Res Int 2015: 842804, 2015.
14. Han, J, Waddington, G, Adams, R, Anson, J, and Liu, Y. Assessing proprioception: A critical review of methods. J Sport Health Sci 5: 80–90, 2016.
15. Han, J, Waddington, G, Anson, J, and Adams, R. Level of competitive success achieved by elite athletes and multi-joint proprioceptive ability. J Sci Med Sport 18: 77–81, 2015.
16. Hari, M, Shibayama, A, Takeshita, D, Hay, DC, and Fukushima, S. A comparison of the mechanical effect of arm swing and countermovement on the lower extremities in vertical jumping. Hum Mov Sci 27: 636–648, 2008.
17. Hillier, S, Imminn, M, and Thewlis, D. Assessing proprioception: A systematic review of possibilities. Neurorehabil Neural Repair 29: 933–949, 2015.
18. Hudson, JL. Performance excellence: Drop, stop, pop: Keys to vertical jumping. Strategies 3: 11–14, 1990.
19. Kai, S, Nakahara, M, Watari, K, Murakami, S, and Yoshimoto, R. Knee joint angle at the time of adjustment to submaximal jumping in healthy men. J Phys Ther Sci 18: 11–13, 2006.
20. Kellis, SE, Tsitskaris, GK, Nikoloudakis, MD, and Mousikou, KC. The evaluation of jumping ability of male and female basketball players according to their chronological age and major leagues. J Strength Cond Res 13: 40–46, 1999.
21. Landis, JR and Koch, GG. An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. Biometrics 33: 363–374, 1977.
22. Lees, A, Vanrenterghem, J, and De Clercq, D. The maximal and submaximal vertical jump: Implications for strength and conditioning. J Strength Cond Res 18: 787–791, 2004.
23. Lees, A, Vanrenterghem, J, and De Clercq, D. The energetics and benefit of an arm swing in submaximal and maximal vertical jump performance. J Sports Sci 24: 51–57, 2006.
24. Lehner, M, Lamrova, I, and Elfmark, M. Changes in speed and strength in female volleyball players during and after a plyometric training program. Acta Universitatis Palackianae Olomucensis. Gymnica 59: 59–65, 2009.
25. Lenberg, KS. Coaching Volleyball: Defensive Fundamentals and Techniques. Monterey, CA: Coaches Choice, 2004.
26. Lloyd, RS, Oliver, JL, Hughes, MG, and Williams, CA. Age-related differences in the neural regulation of stretch–shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol* 22: 37–43, 2012.

27. Markovic, G and Newton, RU. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med* 41: 349–355, 2007.

28. Markovic, G, Jukic, I, Milanovic, D, and Metikos, D. Effects of sprint and plyometric training on muscle function and athletic performance. *J Strength Cond Res* 21: 543–549, 2007.

29. McClay, IS, Robinson, JR, Andriacchi, TP, Frederick, EC, Gross, T, Martin, P, Valiant, G, Williams, KR, and Cavanagh, PR. A profile of ground reaction forces in professional basketball. *J Appl Biomech* 10: 222–236, 1994.

30. McErlain-Naylor, S, King, M, and Pain, MT. Determinants of countermovement jump performance: A kinetic and kinematic analysis. *J Sports Sci* 32: 1805–1812, 2014.

31. Oudejans, RRD, Karamat, RS, and Stolk, MH. Effects of actions preceding the jump shot on gaze behavior and shooting performance in elite female basketball players. *Int J Sports Sci Coaching* 7: 255–267, 2012.

32. Paul, J and Nagarajan, MS. Comparison of proprioception in injured and uninjured knee joints among male professional footballers. *Int J Physiosphere* 2: 361–364, 2015.

33. Perez-Gomez, J and Calbet, JAL. Training methods to improve vertical jump performance. *J Sports Med Phys Fit* 53: 339–357, 2013.

34. Schoenfeld, BJ, Pope, ZK, Benik, FM, Hester, GM, Sellers, J, Nooner, JL, Schnaiter, JA, Bond-Williams, KE, Carter, AS, Ross, CL, Just, BL, Henselmans, M, and Krieger, JW. Longer interset rest period enhance muscle strength and hypertrophy in resistance-trained men. *J Strength Cond Res* 30: 1805–1812, 2016.

35. Sevrez, V and Bourdin, C. On the role of proprioception in making free throws in basketball. *Res Q Exerc Sport* 86: 274–280, 2015.

36. Struzik, S. *Basketball: History, Theory, Didactics*. Kaunas, Lithuania: Lithuanian Academy of Physical Education, 2003.

37. Struzik, A, Rokita, A, Pietraszewski, B, and Popowczak, M. Accuracy of replicating static torque and its effect on shooting accuracy in young basketball players. *Hum Mov* 15: 216–220, 2014.

38. Struzik, A and Zawadzki, J. Leg stiffness during phases of countermovement and take-off in vertical jump. *Acta Bioeng Biomech* 15: 113–118, 2013.

39. Taube, W, Leukel, C, and Gollhofer, A. How neurons make us jump: The neural control of stretch–shortening cycle movements. *Exerc Sport Sci Rev* 40: 106–115, 2012.

40. Van Zandwijk, JP, Bobbert, MF, Munneke, M, and Pas, P. Control of maximal and submaximal vertical jumps. *Med Sci Sports Exerc* 32: 477–485, 2000.

41. Vanrenterghem, J, Lees, A, Lenoir, M, Aerts, P, and De Clercq, D. Performing the vertical jump: Movement adaptations for submaximal jumping. *Hum Mov Sci* 22: 713–727, 2004.

42. Zawadzki, J and Siemieński, A. Maximal frequency, amplitude, kinetic energy and elbow joint stiffness in cyclic movements. *Acta Bioeng Biomech* 12: 55–64, 2010.

43. Zemkova, E, Kyselovičová, O, and Hamar, D. Postural sway response to rebound jumps of different duration. *Hum Mov* 11: 153–156, 2010.