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Muscle Length and Shortening Velocity Changes during the Different Types of Vertical Jumps

Chae, Woen-Sik*(Kyungpook National University)

국문초록

수직점프 동작시 근육길이와 수축속도 변화

채원식*(경북대학교)

본 연구의 목적은 각기 다른 수직 점프 동작 시 근육의 길이와 근육의 수축속도 변화를 비교 분석하는데 있다. 피험자의 운동학적 변인들을 분석하기 위해 2대의 고감도 카메라를 (60 Hz, Panasonic AG455) 사용하여 점프 동작을 촬영하였다. 대퇴직근, 내측광근, 외측광근, 중간광근, 대퇴이두근 (단두), 내측과 외측 비복근의 길이와 근수축 속도는 Brand et al. (1982)에 의해 제시되어진 하지근 기시 정지점의 3차원 좌표값과 동작분석을 통한 하지 분절간의 회전 및 변환행렬을 사용하여 측정되어졌다. 일반적인 근육 길이와 수축속도의 변화 형태는 각기 다른 점프간에 매우 유사한 형태를 보였다. 상승기 초기에 대퇴사두근의 길이가 최대인것으로 나타났으며, 이에 반해 대퇴이두근과 내외측 비복근은 공중 동작이 발생하는 시점에 근의 길이가 최대인 것으로 나타났다. 근육의 길이 변화 범위는 대퇴직근이 35.9에서 47.5 cm, 외측광근이 29.4에서 38.8 cm, 중간광근이 31.5에서

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* Corresponding Author. 교수. 425-791 경기도 안산시 상록구 사1동 1271번지 한양대학교 체육과학대학 생활스포츠학부
연락처 : choiia@hanyang.ac.kr, Tel : 011-315-5742

38.0 cm, 내측광근이 30.9에서 38.6 cm, 대퇴이두근이 21.3에서 39.1 cm, 외측비복근이 31.4에서 33.5 cm, 내측비복근이 30.5에서 33.2 cm인 것으로 나타났다. SQ와 CMJ에서는 대퇴사두근의 최대 단축성 수축 속도와 대퇴이두근과 내외측 비복근의 최대 신장성 수축이 공중동작이 발생하기 바로 전에 이루어졌다. 대퇴사두근의 최대 신장성 수축과 대퇴이두근과 내외측 비복근의 최대 단축성 수축은 일반적으로 피험자가 착지하는 순간에 발생되어졌다. 그러나 HJ와 DJ에서는 대퇴사두근의 최대 신장성 추축과 대퇴이두근과 내외측 비복근의 최대 신장성 수축이 하강기 초반에 발생되어졌다.

KEY WORDS : MUSCLE, VERTICAL JUMP, CONTRACTION

I. Introduction

For almost a century, it has been known that the force developed by a muscle during isometric contraction varies with its length. Blix (1895), using isolated frog muscles, first demonstrated the relationship between the length of a muscle and the tension it could generate when contracting. The classic experiment by Gordon, Huxley, and Julian (1966) demonstrated that the tension developed in isolated fibers of a frog skeletal muscle depended on its sarcomere length. The results of their study were in close agreement with the theoretical predictions that were based on the cross-bridge theory (Huxley, 1957), and they helped to establish the cross-bridge theory as the primary paradigm to describe muscular force production.

According to the cross-bridge theory, cross-bridges extend from the thick to thin filaments and cause sliding of the myofilaments past one another. Since then, many investigators have proposed models to describe the relationship between myofilament overlap and tension generation, which we refer to as the active force-length (F-L) relationship. It has been demonstrated in experiments using isolated muscles that the active tension developed under a tetanus stimulation is maximum at the optimum length and decreases with longer or shorter lengths (Gordon et al., 1966).

Unlike the F-L relationship, the force-velocity (F-V) relationship does not have a precise, anatomically identifiable basis. The F-V relationship states that the force generated by a muscle is a function of its shortening velocity. The F-V relationship proposed by Hill (1938) still serves as the most convenient mathematical description of muscle contraction today. The hyperbolic relationship exists between muscle tensile force and shortening velocity can be explained using the cross-bridge theory (Huxley, 1957). Winter (1979) suggested that as the tension demands of the muscle increase the effective cycling of the cross-bridge elements decreases, resulting in a decreased velocity of shortening.

The force generated by skeletal muscle varies with muscle length and velocity. An understanding of the muscle length and velocity changes that occur during movement provides insights into the physiological importance of this relationship and may provide insights into the design of certain muscle/joint combinations. To accurately evaluate muscle force, the muscle length and velocity changes associated with the performance should be measured and their effects need to be evaluated. The purpose of this study was to give a time varying description of the muscle length and velocity changes during the different jump types.

Ⅱ. Procedures

1. Participants

Eight males with no known musculoskeletal disorders were recruited as the participants. The participants were university students who exercise regularly.

2. Experimental Setup

In order to motivate the participants to perform the jumps with maximum effort, a volleyball was hung at a height of 61 cm above their standing reach heights. Two S-VHS camcorders (Panasonic AG455, 60 fields/s) were used to record the takeoff and landing of the participants. The first camera was placed directly in front of the participant 15 m from the force platform. The second camera was placed 10 m to the side of the right force platform. For spatial reference, a Peak calibration frame (2 m X 2 m X 2.3 m object space, 25 control points) was videotaped at the beginning of each data collection session.

3. Trials

After a 5-min warm-up on a bicycle ergometer, the participant was asked to perform four types of vertical jump with maximum effort in random order:

1) squat jump (SJ) - a squat position was adopted when the jump was initiated.
2) countermovement jump (CMJ) - a lowering of the body preceding the jump (countermovment) performed from a standing posture.
3) hop jump (HJ) - a one step approach followed by a countermovement jump.
4) drop jump (DJ) - a jump performed immediately after landing from a drop height of 0.4 m.

Each participant was instructed on how to perform the different types of jump and allowed enough supervised practices to comfortably perform them within the specific constraints.

4. Data Reduction

For each trial being analyzed, five critical instants were identified from the video recordings except for squat jumps : (a) beginning of the descending limbs in CMJ, the instant when the downward motion first occurs (the highest position of the mid-hip), or the instant of touchdown in HJ and DJ, (b) beginning of the ascending limbs, the instant when the upward motion first occurs (the lowest position of the mid-hip), (c) takeoff from the force platform, (d) landing, the instant when the right foot lands on the force platform, (e) the instant when the mid-hip reaches the lowest position after landing.

For the purpose of this study, each jump was broken into consecutive phases : (a) the descending phase (from either starting position or the instant of touchdown to the lowest position of the mid-hip), not applicable to SQ; (b) the ascending phase (from the lowest position of the mid-hip to takeoff); (c) the flight phase (from takeoff to landing); (d) the landing phase (from landing to lowest mid-hip position).

5. Kinematics

For each selected trial, two -dimensional coordinates of eight body landmarks and two reference markers were manually extracted from video pictures using a Peak 5 motion measurement system (Peak Performance Technologies, Englewood, Co). The landmarks of interest were the right toe, heel, ankle, knee, hip, and anterior superior iliac spine, midpoint between the left and right pubic tubercles and midpoint between the left and right anterior superior spines. Two reference markers on short sticks were secured on the lateral side of the right thigh and shank, respectively. The locations of these markers were used for defining local reference frames. The Direct Linear Transformation (DLT) technique (Abdel-Aziz & Karara, 1971) was used to obtain three-dimensional (3-D) coordinates of selected body landmarks. To minimize the noise due to digitizing errors and skin movements, the 3-D coordinates were filtered using a second order, 6 Hz low pass Butterworth filter. All smoothed coordinates were transformed from the calibration reference frame to the global reference frame, which was located at the rear left corner of the master force platform. In this study the mechanical system of interest was composed of four rigid body segments corresponding to the pelvis, right thigh, shank, and foot. Each segment was considered symmetrical about its longitudinal axis, which was defined as a vector directed from its proximal endpoint to distal endpoint (from the heel to the toe for the foot).

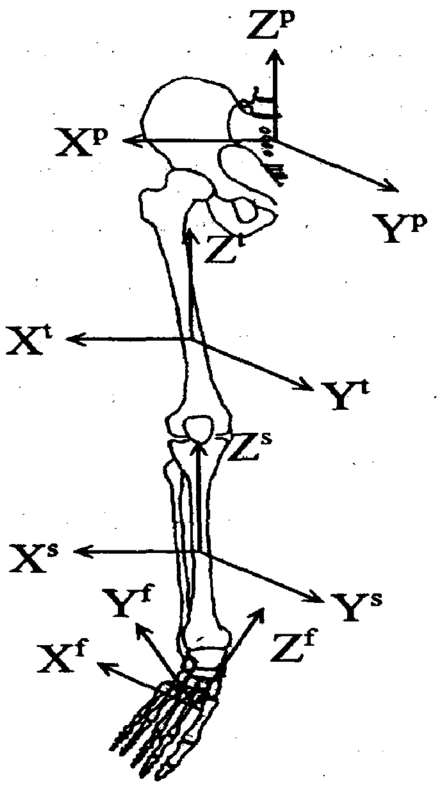

Figure 1. Pelvic, femur, tibia, and foot embedded coordinate systems. Xf, Yf, and Zf: the vectors representing the principal axes of the foot reference frame, Xs, Ys, and Zs: the vectors representing the principal axes of the tibial reference frame, Xt, Yt, and Zt: the vectors representing the principal axes of the femoral reference frame. Xp, Yp, and Zp: the vectors representing the principal axes of the pelvic reference frame.

1) Coordinate Systems

Four local reference frames (Cartesian coordinate systems) were embedded in the pelvis, right femur, tibia and foot, respectively (Figure 1). These local coordinate systems were used to define the locations and orientations of muscles as well as joint orientations. The orientation of a body segment was described in terms of its Eulerian angles with respect to the global reference frame. The origin of each local reference frame was located at the center of gravity (CG) of each segment. For each local reference frame, the first axis (z-axis) was selected with the goal of maximizing the distance between the two landmarks defining the vector.

The second axis (y-axis) was obtained as a line normal to the first axis and passing through the third landmark for that body segment. The third axis (x-axis) was obtained as the cross product of the first two axes. The positive direction of each axis was defined in reference to the standard anatomical position. The positive x-axis was directed from lateral to medial. The positive y-axis extended from posterior to anterior. The positive z-axis extended from distal to proximal.

2) Coordinate Transformation

The knee joint model used in this study included seven muscles (rectus femoris: RF, vastus intermedius: VI, vastus lateralis: VL, vastus medialis: VM, biceps femoris: BF, medial gastrocnemius: GM and lateral gastrocnemius: GL). Three dimensional coordinates of the origins and insertions from Brand, Crowninshield, Wittstock, Pedersen, Clark, and van Krieken (1982) were used in this study. They reported coordinates of the insertions and origins of lower extremity muscles using right-handed orthogonal and anatomically based reference frames. The origin and insertions are represented as three-dimensional coordinates relative to onof the three reference frames fixed to the pelvis, femur or tibia.

Table 1. Coordinates of Muscle Origins and Insertions

Muscle	Origin (mm)				Insertion (mm)			
	Reference frame	X	Y	Z	Reference frame	X	Y	Z
RF	Pelvis	32.6	32.3	17.4	Tibia	4.0	408.4	-0.6
VM	Femur	4.3	188.0	8.8	Tibia	-7.9	399.6	-13.7
VI	Femur	23.2	206.7	17.6	Tibia	-1.8	411.0	0.6
VL	Femur	1.0	212.7	36.5	Tibia	8.9	405.0	15.1
BF	Femur	-0.7	178.4	14.4	Tibia	-38.4	332.3	43.3
MG	Femur	-20.4	7.7	-15.7	Tibia	-36.8	-42.9	2.8
LG	Femur	-19.8	4.8	22.6	Tibia	-36.9	-43.0	2.8

The coordinates of the origin and insertion of each muscle were transformed from the reference frames used by Brand et al. (1982) to the femoral reference frame defined in this study (Table 1). Two different sets of coordinate transformations were performed so that the origin and insertion coordinates of each muscle were expressed relative to the femoral reference frame located at the center of the knee joint (Figure 2).

$$P_{new} = [\mathbf{R}_{p/t}]^t[\mathbf{r}_{n/H}] + [\mathbf{r}_{H/K}]$$
$$S_{new} = [\mathbf{R}_{s/t}]^t\{[\mathbf{r}_{A/K}] + [\mathbf{r}_{m/A}]\}= [\mathbf{R}_{s/t}]^t[\mathbf{r}_{m/K}]$$

where P_{new} and S_{new} are coordinates relative to the femoral reference frame after transformation from the pelvis and shank reference frames, respectively. $R_{p/t}$ and $R_{s/t}$ are rotational matrices of the pelvic reference frame and the shank reference frame relative to the femoral reference frame. The rotation matrix was obtained using the dot products of the corresponding unit vectors representing the principal axes of the two reference frames. $r_{A/K}$ is the translation matrix from the knee joint center to the ankle joint center. $r_{m/A}$ is the translation matrix from the ankle joint center to an attachment location of a muscle in the shank segment. $r_{m/K}$ is the translation matrix from the knee joint center to a muscle attachment location in the shank segment. $r_{n/H}$ is the translation matrix from the hip joint center to the location of a muscle attachment in the pelvic segment. $r_{H/K}$ is the translation matrix from the knee joint center to the hip joint center.

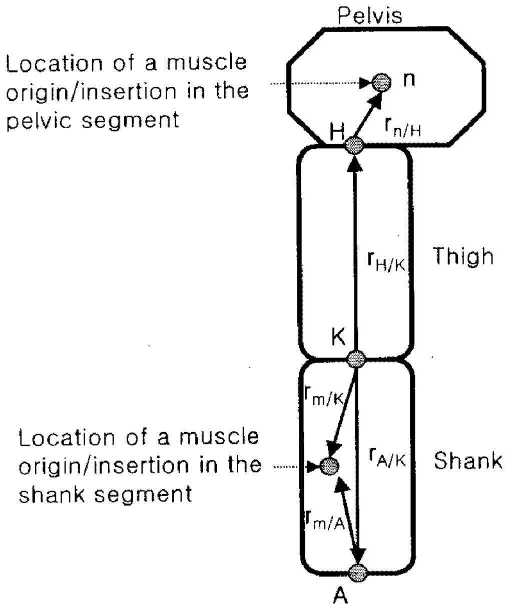

Figure 2. A Schematic Illustrating the Coordinate Transformation.

3) Muscle Length

As in most studies using the technique of musculoskeletal modeling,the straight line approach was used to represent the line of action of a muscle force in this study. When determining muscle lengths, all coordinates involved were transformed such that all coordinates are relative to the femoral reference frame. Once the origin (X_o) and insertion (X_i) were expressed relative to the femoral reference frame, the muscle length (L_m) was calculated as:

$$L_m = |X_i - X_o|$$

4) Muscle Shortening Velocity

Seven sets of muscle length-time (L-t) data, one for each muscle, were acquired for each trial.

The central difference method (Wood, 1982) was used to obtain shortening velocity-time (v-t) data. Knowing the time histories of individual muscle lengths, the shortening velocity

$$V_m^i = (L_m^{i+1} - L_m^{i-1}) / 2\Delta t$$

where i denotes a frame number and Δt is the time elapsed between consecutive frames (1/60 s).

Ⅲ. Results and Discussion

1. Muscle Length

Normalized mean lengths of individual muscles during the CMJ are presented in Figure 3. As mentioned previously, the knee extends and the ankle plantar flexes simultaneously, the lengths of both GL and GM were nearly constant. The profile and magnitude for each muscle length were similar for all different jump types.

The minimum and maximum muscle lengths during different jump types are shown in Table 2. The muscle lengths across different jump types ranged from 35.9 to 47.5, 29.4 to 38.6, 31.5 to 37.7, 30.9 to 38.4, 21.6 to 39.1, 31.4 to 33.4, and 30.5 to 33.2 cm for the RF, VL, VI, VM, BF, GL, and GM, respectively. The maximum muscle lengths for the quadriceps occurred at the beginning of the ascending phase, while the BF, GL, and GM reached their maximum lengths at the instant of takeoff.

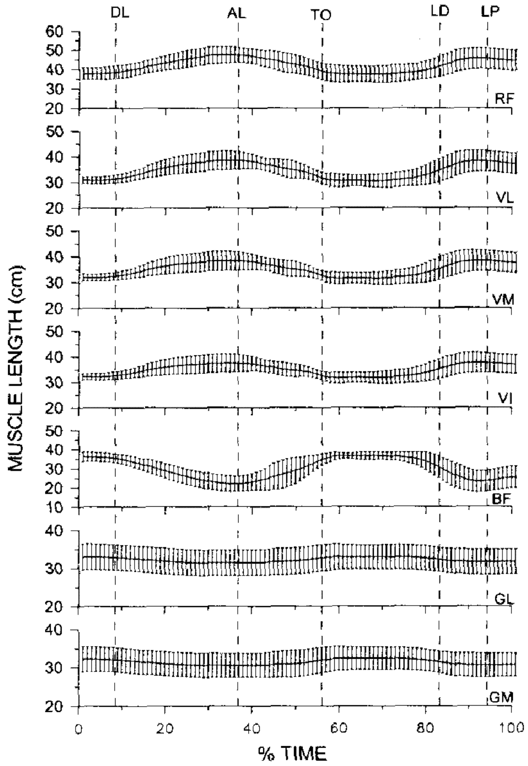

Figure 3. Normalized mean lengths of individual muscles during the CMJ.

Table 2. Average Minimum and Maximum Muscle Length (cm) During the Different Jump Types

Jump Type	RF		VL		VI		VM		BF		GL		GM	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
SQ	35.9	45.7	29.4	37.4	31.5	37.1	30.9	37.6	22.0	37.2	31.4	33.0	30.6	32.5
CMJ	37.4	47.5	30.4	38.5	31.6	37.7	31.5	38.3	22.1	37.6	31.4	33.0	30.5	32.4
HJ	37.6	46.3	30.1	37.9	32.0	37.6	31.4	38.0	22.4	37.0	31.5	33.0	30.5	32.5
DJ	38.0	46.9	30.6	38.6	32.1	37.7	3.7	38.4	21.6	39.1	31.5	33.4	30.6	33.2

The straight line approach may not be applicable in some instants for the determination of muscle line of action and its length. For example, Chow (1994) reported that the quadriceps tendon started to wrap around the femoral groove at 55° knee flexion angle (KFA). Underestimated quadriceps length will be obtained using the straight line approach at large KFAs. A modification should be made in defining the muscle length and line of action in this situation.

2. Muscle Shortening Velocity

Normalized mean shortening velocities of individual muscles during the CMJ are presented in Figure 4. The temporal patterns of muscle shortening velocity were fairly consistent across different jump types. In the present study, a muscle shortening velocity is normalized using the optimum muscle length (Lo/s). Because the maximum overlap of thick and thin filaments occurred at sarcomere lengths of 2.64 and 2.81 μm (Walker & Schrodt, 1973), the optimum fiber length (Lo) was computed as the product of the number of sarcomere per fiber and 2.72 μm. For each muscle, the number of sarcomere per muscle fiber was calculated by dividing muscle fiber length at the anatomical position by the sarcomere length at the anatomical position from Cutts (1988).

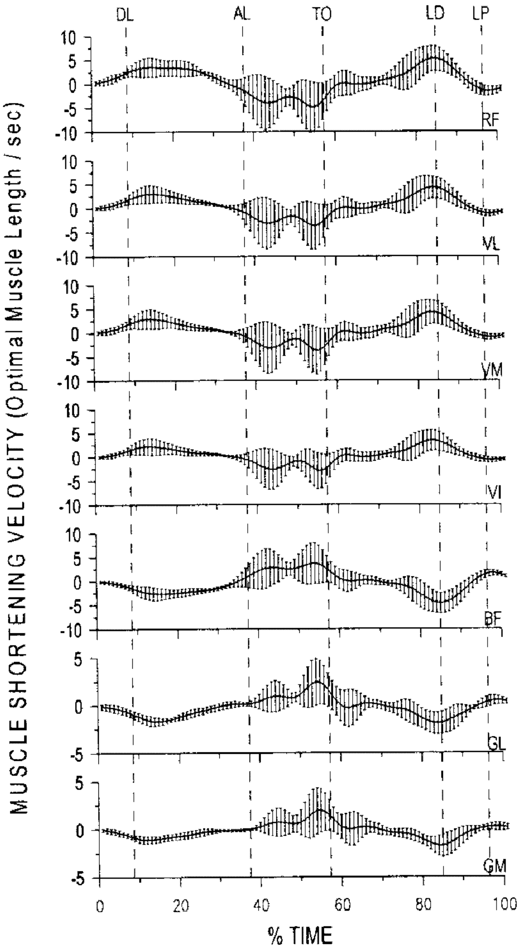

Figure 4. Normalized mean shortening velocities of individual muscles during the CMJ.

Table 3. Average Maximum Concentric and Eccentric Muscle Shortening Velocities (optimum muscle length per second) During the Different Jump Types

Jump Type	RF		VL		VI		VM		BF		GL		GM	
	Con[a]	Ecc[b]	Con	Ecc	Con	Ecc	Con	Ecc	Con	Ecc	Con	Ecc	Con	Ecc
SQ	3.6	2.8	2.7	2.5	1.8	1.7	2.4	2.4	2.5	3.1	2.2	2.4	1.3	1.6
CMJ	6.3	3.0	5.6	2.7	4.1	1.5	5.2	2.2	3.0	5.1	2.7	3.6	1.9	2.3
HJ	4.5	3.4	4.1	3.5	2.5	2.0	3.5	2.8	3.5	4.3	2.6	3.1	1.7	2.7
DJ	6.6	5.6	5.9	5.5	4.3	3.7	5.6	4.9	5.0	4.6	3.2	3.4	1.9	1.9

Note. [a]Concentric contraction. [b]Eccentric contraction

Table 3 presents the maximum concentric and eccentric muscle shortening velocities across different jump types. The maximum concentric muscle shortening velocities across all conditions were 6.6, 5.9, 4.3, 5.6, 5.0, 3.2, and 1.9 Lo/s for the RF, VL, VI, VM, BF, GL, and GM, respectively. The maximum eccentric muscle shortening velocities observed in this study across different jump types were 5.6, 5.5, 3.7, 4.9, 5.1, 3.6, and 2.7 Lo/s for the RF, VL, VI, VM, BF, GL, and GM, respectively. The peak concentric shortening velocities for the quadriceps and eccentric shortening velocities for the BF, GL, and GM were observed immediately before the takeoff during SQ and CMJ. The peak eccentric shortening velocities for the quadriceps and concentric shortening velocities for the BF, GL, and GM generally occurred at the instant of landing. However, the peak eccentric shortening velocities for the quadriceps and concentric shortening velocities for the BF, GL, and GM were observed at the beginning of the descending phase for HJ and DJ.

Muscle shortening velocities during walking reported by Pierrynowski (1982) were calculated to be 3.6 and 2.7 Lo/s for concentric and eccentric contractions, respectively. Because the walking motion is much slower than the jumping action, lower muscle shortening velocities in walking are expected.

The coordinate data on muscle origins and insertions were usually based on information available in the literature. Because most data in the previous studies were measured from different cadaver specimens, the coordinate data showed many variations. Because the muscle length is directly determined by subtracting origin from insertion, the magnitude of muscle length is very sensitive to changes in the coordinate data. To avoid possible errors, effort should be made to gather the realistic muscle coordinate data in vivo. Another problem in estimating muscle length is that subtle internal length changes are not registered as a change in the muscle origin-insertion distance. Voigt et al. (1994) reported that when a musculotendon unit resists a stretch by contracting eccentrically, the stretch is imposed on the tendon but not the muscle. Similar difficulties may be found in biarticular muscles such as the rectus femoris and gastrocnemius. For example, as the knee extends and the ankle plantar flexes simultaneously, the length of the gastrocnemius muscle remains relatively unchanged. In a similar manner, as the hip extends and the knee extends, the length of the rectus femoris muscle remains essentially unchanged. If these undetected subtle stretches occur within or outside of the muscle, the model will have some degree of error in estimating either muscle length or muscle velocity changes.

Conclusion

1. The maximum muscle lengths for the quadriceps occurred at the beginning of the ascending phase, while the BF, GL, and GM reached their maximum lengths at the instant of takeoff.
2. The peak concentric shortening velocities for the quadriceps and eccentric shortening velocities for the BF, GL, and GM were observed immediately before the takeoff during SQ and CMJ. The peak eccentric shortening velocities for the quadriceps and concentric shortening velocities for the BF, GL, and GM generally occurred at the instant of landing. However, the peak eccentric shortening velocities for the quadriceps and concentric shortening velocities for the BF, GL, and GM were observed at the beginning of the descending phase for HJ and DJ.

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