Vertical Jumping Reorganization With Aging: A Kinematic Comparison Between Young and Elderly Men

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To our knowledge jumping kinematics have never been studied in elderly persons. This study was aimed at examining the influence of aging on vertical jump performance and on interjoint coordination. Two groups of adults, 11 young men ages 18–25 years and 11 older men ages 79–100 years, were filmed while performing a maximal squat jump. Compared to young adults, jump height was significantly decreased by 28 cm in the elderly. Older adults spontaneously jumped from a more extended position of the hip. Results showed a decrease in hip, knee, and ankle linear velocity and angular amplitude with aging. The decrease in jump height was attributed to a decrease in explosive force and in the range of shortening of extensor muscles. In agreement with the literature, a proximo-distal coordination pattern was observed in young adults. Older adults used a simultaneous pattern. This may indicate that adults adjust their pattern of joint coordination as they age.

Key Words: squat jump, age, biomechanics

The push-off kinematics of vertical jumping in young adults has been studied extensively over the past decades (Aragón-Vargas & Gross, 1997; Bobbert & Van Ingen Schenau, 1988; Gregoire, Veeger, Huijing, & Van Ingen Schenau, 1984; Hudson, 1986; Vanrenterghem, Lees, Lenoir, Aerts, & De Clercq, 2004). However, investigations of the push-off kinematics of vertical jumping in older persons, to our knowledge, have not been published. Aging has been shown to cause a significant decline in jumping performance (Bosco & Komi, 1980). Although the lowered capacity of elderly persons to develop explosive force has been demonstrated in vertical jumping tasks (Bosco & Komi, 1980; Izquierdo, Aguado, Gonzalez, Lopez, & Hakkinen, 1999), none of these studies examined changes in lower limb joint kinematics in aged adults.

Many studies carried out with young adults have demonstrated that maximizing jump performance requires a specific coordination of body segments. A
proximal-to-distal pattern has been identified as optimal for reaching a maximal body mass center linear velocity at takeoff (Bobbert & Van Soest, 2001). Bobbert and Van Soest emphasized the importance of increasing the range over which extensor muscles can produce maximal force at the greatest shortening velocity. A sequential pattern of coordination prevents a premature takeoff, allowing lower limb joints to almost fully extend and produce greater work. By comparing young children age 3 years with young adults, it has been found that the proximo-distal coordination pattern is stabilized early in development (Clark, Phillips, & Petersen, 1989). One question of interest therefore is whether the sequential organization of joint movements is modified with changes of the musculoskeletal system associated with aging. For instance, the loss of power (Bosco & Komi, 1980; Valour, Ochala, Ballay, & Pousson, 2003) and joint flexibility (Such, Unsworth, Wright, & Dowson, 1975), and the increasing difficulty of maintaining balance (Lord, Clark, & Webster, 1991; Maki & McIlroy, 1996), are likely to force a reorganization of the jumping movement.

Therefore the goal of this study was to determine the influence of aging on squat jump performance, and more particularly on interjoint coordination through kinematic analysis. Considering the demands of the task, that is, to start from a position of equilibrium and increase the vertical velocity of the body mass center throughout the push-off, it was hypothesized that, with increasing age, the loss of muscle strength mainly limits squat jump performance and modifies the sequential type of coordination commonly used by young adults to propel themselves vertically into the air.

**Methods**

Two groups of men, 11 per group, volunteered to participate in this study. Before the test each one signed an informed consent form. The first group was composed of student athletes who had skills in jumping tasks as gymnasts, soccer players, and handball players. They ranged in age from 18 to 25 years (mean age 22.1 ± 4.4 yrs; height 1.74 ± 0.05 m; body mass 66.8 ± 7.2 kg). The second group was composed of elderly men who ranged in age from 79 to 100 years (mean age 82.6 ± 7.8 yrs; height 1.67 ± 0.04 m; body mass 63.3 ± 10.3 kg). Exclusion criteria for participation in this study included orthopedic or neurological pathologies of the upper or lower limbs. The elderly all practiced physical activities such as swimming or cycling every day. At the beginning of the testing session, the participants followed a standardized warm-up routine and performed a few practice jumps before the test. Afterward they each performed two squat jumps without preparatory countermovement. The initial angle of the knees before push-off was fixed at a position of 100°. The participants were instructed to keep their hands on their hips and jump as high as possible. The best of the two trials based on maximum jump height was selected for analysis.

Landmarks were placed on the left side of the body over the 5th metatarsophalangeal joint, lateral malleolus, lateral femoral epicondyle, greater trochanter, and acromion. Similar to previous studies from the literature (Bobbert & Van Ingen Schenau, 1988; Gregoire et al., 1984; Pandy & Zajac, 1991), the squat jump movement was assumed to be symmetric and the left and right lower limbs were considered as one segment. The body was modeled in two dimensions with four segments: feet, legs, thighs, and upper body (head-arms-trunk [HAT]). During
jumping, the participants were filmed in the sagittal plane with a video camera recorder operating at a nominal frame rate of 60 Hz. The optical axis of the camera was perpendicular to the plane of motion. The films were then digitized frame by frame using a specific motion analyzer (Kinematic Analysis software, version 4.0, developed by R.E. Schleihauf of San Francisco State University) (Schleihauf, Gray, & De Rose, 1983).

Absolute coordinates of the landmarks were extracted from video film and then smoothed using an interpolation function that fitted cubic spline polynomials between successive data points (De Boor, 1978). In combination with anthropometric data from Winter (1990), the absolute joint coordinates were used to determine the position of each segment mass center as well as the position of the body mass center (BMC). The BMC is the point at which all the body segments’ mass seems to be concentrated. The horizontal ($x_{BMC}$) and vertical ($y_{BMC}$) coordinates of the BMC were determined using the so-called segmental method by application of the following equations:

\[ x_{BMC} = -\frac{1}{M} \sum_{i=1}^{4} m_i x_i \]  
\[ y_{BMC} = -\frac{1}{M} \sum_{i=1}^{4} m_i y_i \]  

where $M$ is the body mass, $m_i$ is the mass of the $i$-th segment, and $x_i, y_i$ are the horizontal and vertical coordinates of the mass center of the $i$-th segment, respectively.

Jump height was calculated from the difference between the height of the body mass center at the apex of the jump and its height when the participant was standing upright with heels on the ground. Joint angles were determined and then differentiated as a function of time to yield joint angular velocities. Joint amplitude was calculated from the difference between the joint angular positions at takeoff and at the start of the push-off. The timing at which the hip, knee, and ankle joints began to rotate was also analyzed. The beginning of joint extension was detected when joint angular velocity started to be positive.

Although this study was not aimed at performing a postural analysis on two age categories of individuals executing a vertical jump, the control of equilibrium was evaluated by examining the projection of the BMC on the horizontal axis of the supporting base.

The vertical velocities of the lower limb joints and the HAT center of mass were calculated from the first derivative of their vertical displacement. The differences between the vertical velocity of the HAT center of mass ($\dot{y}_{HAT}$) and the vertical velocities of the hip ($\dot{y}_H$), knee ($\dot{y}_K$), and ankle ($\dot{y}_A$) were studied so we could determine the pattern of joint coordination (Bobbert & Van Ingen Schenau, 1988). This method allows for the assessment of hip, knee, and ankle contributions to the vertical velocity of the HAT center of mass. Achieving a high vertical velocity of the HAT center of mass is of critical importance for jump height because it contributes predominantly to the vertical velocity of the BMC (Bobbert & Van Ingen Schenau, 1988). For clearer readability, $\dot{y}_{HAT} - \dot{y}_H$, $\dot{y}_{HAT} - \dot{y}_K$, and $\dot{y}_{HAT} - \dot{y}_A$ will be referred to as the relative velocity of the hip, knee, and ankle, respectively. Subsequently, we determined the instant at which the lower limb joint relative velocities reached their peak.
The mean and standard deviation values were calculated for all the studied parameters. Because the assumption of normality of distribution was not met, each variable was compared between the two groups of participants using the Mann-Whitney U test. Statistical significance was accepted at the $p < 0.05$ level. In order to display mean time-series data, we normalized kinematic data ($t = 0$, the instant the BMC reached its lowest position, and $t = 100\%$, the instant at which the toes lost contact with the floor). Mean curves were obtained for each experimental group by averaging individual time-series data.

**Results**

Figure 1 presents stick figures for a representative person of each experimental group executing a maximal squat jump.

The young men jumped on average 28 cm higher than the elderly men, $p < 0.001$ (Table 1). Jump heights ranged from 28 to 45 cm in young men and from 2 to 11 cm in elderly men. The total duration of the push-off phase was on average 0.1 s longer in older ($0.42 \pm 0.07$ s) than in younger men ($0.32 \pm 0.07$ s), $p < 0.01$.

Although the difference was not significant, the initial vertical position of the BMC was found to be higher for the elderly than for the young group ($42 \pm 3\%$ and $38 \pm 3\%$ of the participant’s height, respectively). The initial horizontal position of the BMC relative to the foot differed significantly between groups, $p < 0.001$. The projection of the BMC relative to the foot was indeed located on average 3 ± 2 cm behind the toes in young men; in older men it was located 15 ± 3 cm behind the toes. Figure 2 shows the position of the BMC relative to the foot expressed as
a percentage of the foot segment length. The BMC was located at 25 ± 16% of the foot length in young men, with 0% corresponding to the metatarsophalangeal joint. In the elderly the projection of the BMC relative to the foot was close to the ankle joint, on average at 83 ± 7% of the foot length.

The horizontal displacements of the BMC in the sagittal plane throughout the push-off for a representative young adult and older adult are illustrated in Figures 1b and 1d, respectively. From the start of the push-off to the instant of takeoff, the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Young</th>
<th>Elderly</th>
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<tbody>
<tr>
<td>Jump height (m)</td>
<td>0.37 ± 0.07</td>
<td>0.09 ± 0.03**</td>
</tr>
<tr>
<td>Push-off duration (s)</td>
<td>0.32 ± 0.07</td>
<td>0.42 ± 0.07**</td>
</tr>
<tr>
<td>$\theta_H$ amplitude (rad)</td>
<td>1.27 ± 0.14</td>
<td>0.99 ± 0.24*</td>
</tr>
<tr>
<td>$\theta_K$ amplitude (rad)</td>
<td>1.18 ± 0.19</td>
<td>1.04 ± 0.16</td>
</tr>
<tr>
<td>$\theta_A$ amplitude (rad)</td>
<td>1.06 ± 0.28</td>
<td>0.70 ± 0.24*</td>
</tr>
<tr>
<td>$\theta_H$ initial (rad)</td>
<td>1.62 ± 0.07</td>
<td>1.74 ± 0.14*</td>
</tr>
<tr>
<td>$\theta_K$ initial (rad)</td>
<td>1.81 ± 0.21</td>
<td>1.74 ± 0.13</td>
</tr>
<tr>
<td>$\theta_A$ initial (rad)</td>
<td>1.59 ± 0.18</td>
<td>1.56 ± 0.13</td>
</tr>
<tr>
<td>$\theta_H$ takeoff (rad)</td>
<td>2.91 ± 0.11</td>
<td>2.73 ± 0.10*</td>
</tr>
<tr>
<td>$\theta_K$ takeoff (rad)</td>
<td>2.99 ± 0.09</td>
<td>2.78 ± 0.12**</td>
</tr>
<tr>
<td>$\theta_A$ takeoff (rad)</td>
<td>2.65 ± 0.21</td>
<td>2.26 ± 0.14**</td>
</tr>
<tr>
<td>$\theta_H$ max (rad·s$^{-1}$)</td>
<td>9.8 ± 0.9</td>
<td>6.9 ± 1.3**</td>
</tr>
<tr>
<td>$\theta_K$ max (rad·s$^{-1}$)</td>
<td>12.4 ± 1.6</td>
<td>8.1 ± 2.2**</td>
</tr>
<tr>
<td>$\theta_A$ max (rad·s$^{-1}$)</td>
<td>15.4 ± 2.5</td>
<td>10.5 ± 2.6*</td>
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* $p < 0.01$; ** $p < 0.001$

5th metatarsophalangeal Lateral malleolus

Figure 2 — Vertical projection of body mass center on the foot in the starting position for the young and elderly groups (0% and 100% corresponding to the 5th metatarsophalangeal and lateral malleolus joints, respectively). ◯ Vertical projection of BMC for one participant. ● Average vertical projection of BMC on the foot.
BMC moved forward. At the instant of takeoff, the BMC of young jumpers was found to lie exactly above the metatarsophalangeal joint (on average 0 ± 2 cm) whereas it was located 12 ± 3 cm behind the toes in the elderly. The net horizontal displacement calculated from the difference between the BMC horizontal position at the start of the push-off and at takeoff was equivalent between the two groups (3 ± 2 cm for young men and 3 ± 3 cm for the elderly).

Joint angle time histories are shown in Figure 3. Ankle and knee initial positions were similar for both groups of participants (Figure 3 and Table 1). However, the older men started to jump from a more extended position of the hip than did the young men, \( p < 0.01 \). This caused the hip angle trajectory to be different from the start of the push-off between the two groups.

The maximal angular velocities of each lower limb joint were greater in young than in older men, \( p < 0.01 \). The hip and ankle angular amplitudes were significantly lower in the elderly, \( p < 0.01 \) (Table 1). Although knee amplitude was reduced in the elderly, this difference was not found to be significant, \( p = 0.08 \). The hip, knee, and ankle angles plateaued before takeoff in the elderly (Figure 3) and reached their final position before that instant. The temporal delay between the instant of the beginning of hip and knee extensions was equivalent between the two groups (Figure 4). However, ankle extension began later relative to knee extension in the elderly compared to the young men, \( p < 0.001 \).

Hip, knee, and ankle angles were greater in young men than in the elderly at the very end of the push-off. With regard to takeoff position, it was found that the hip, knee, and ankle final angles were significantly smaller in older than in younger men, \( p < 0.01 \) (see Table 1 and Figure 3).

Analysis of the timing at which \( \dot{\gamma_{HAT}} - \dot{\gamma_{H}}, \dot{\gamma_{HAT}} - \dot{\gamma_{K}}, \) and \( \dot{\gamma_{HAT}} - \dot{\gamma_{A}} \) reached their peak showed that the joint coordination pattern differed between the young and elderly participants. A proximo-distal pattern of coordination was identified when the peak relative velocity of the hip occurred before that of the knee, which in turn occurred before that of the ankle. Such a sequential pattern was significantly used by young men, \( p < 0.05 \), while the peak relative velocities of the hip, knee,
and ankle occurred simultaneously in the elderly (Figure 5 and Table 2). The peak value of $y_{HAT}$, $y_{HAT} - y_H$, $y_{HAT} - y_K$, and $y_{HAT} - y_A$ were significantly lower, $p < 0.001$ (Figure 5) and appeared earlier in the push-off in elderly than in young men, $p < 0.001$ (Table 2).

Discussion

The goal of this study was to examine the modifications of jumping performance and more specifically of interjoint coordination with aging. Jumping height was found to be greatly lowered in elderly participants. The reduced performance was reflected by a lowered linear velocity of the HAT segment which contributes predominantly to the linear velocity of the BMC (Bobbert & Van Ingen Schenau, 1990).
The linear velocity of the BMC is directly related to joint angular velocities. Increasing the linear velocity of the BMC is only possible by the transformation of body segment rotation into translation of the BMC (Bobbert & Van Soest, 2001; Van Ingen Schenau, 1989). Results revealed a significant decrease of maximal hip, knee, and ankle angular velocities with aging. This indicates a loss of explosive force production in the elderly which is in accordance with previous literature (Bosco & Komi, 1980; Izquierdo et al., 1999). The decrease of explosive force was also reflected by a lengthened duration of the push-off phase.

Besides the decrease in explosive force, findings indicate that the reduction of joint amplitude also causes the jump performance to be impaired with aging. The reduced angular range of motion diminishes the shortening distance of extensor muscles. The early reach of the final position shows that the elderly do not take advantage of the entire range of motion available to further increase the BMC velocity. This is confirmed by the large and early decrease of HAT center-of-mass velocity before the instant of takeoff and the early decrease of the relative velocity of the hip, knee, and ankle joints. This arrangement might prevent joint damage at the end of the push-off and could also help control balance during the subsequent flight and landing phases.

A different spatio-temporal organization of movement was found between the two age categories. In agreement with previous literature, young jumpers exhibited a proximo-distal coordination pattern (e.g., Bobbert & Van Ingen Schenau, 1988; Gregoire et al., 1984). A simultaneous coordination was observed in the elderly. A proximo-distal mode of coordination has been identified in several studies in which participants were free to jump from their preferred position (Bobbert & Van Ingen Schenau, 1988; Gregoire et al., 1984; Rodacki, Fowler, & Bennett, 2002; Van Soest, Bobbert, & Van Ingen Schenau, 1994). Nevertheless, because of some differences in the initial conditions of the jump between the two groups, one should be cautious about making a direct comparison of joint coordination patterns used by young and older adults.

It was indeed found that the elderly jumped from a more extended hip angle while the initial ankle and knee angles were not different, due to the testing protocol which fixed the starting knee angle only. It appears from present data that because of

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<tr>
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<th>$t\hat{y}_{HAT} - \hat{y}_H$</th>
<th>$t\hat{y}_{HAT} - \hat{y}_K$</th>
<th>$t\hat{y}_{HAT} - \hat{y}_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Young</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(s)</td>
<td>0.22 ± 0.02</td>
<td>0.25 ± 0.01</td>
<td>0.27 ± 0.02</td>
</tr>
<tr>
<td>(%)</td>
<td>68 ± 6</td>
<td>78 ± 3</td>
<td>84 ± 6</td>
</tr>
<tr>
<td><strong>Elderly</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(s)</td>
<td>0.26 ± 0.02</td>
<td>0.25 ± 0.04</td>
<td>0.26 ± 0.03</td>
</tr>
<tr>
<td>(%)</td>
<td>62 ± 5</td>
<td>59 ± 9</td>
<td>63 ± 7</td>
</tr>
</tbody>
</table>

*Note: Time is expressed in absolute (s) and relative (% of total duration of the push-off) values.*
the need to maintain equilibrium and the different strength capacities of the young and elderly, the elderly spontaneously adopted a distinct starting position to perform a maximal squat jump. This is likely attributable to a decline of isometric force in the lower extremities with aging (Bazzucchi, Felici, Macaluso, & De Vito, 2004; Connelly, Rice, Roos, & Vandervoort, 1999; Roos, Rice, Connelly, & Vandervoort, 1999; Vandervoot & McComas, 1986). The difference in starting hip angle results in a shift of the vertical projection of the BMC in the elderly relative to the foot toward the ankle joint. This may also reflect a strategy on the part of the elderly to keep themselves from falling by locating the BMC at a greater distance from the foot center of rotation (i.e., metatarsophalangeal joint) than young jumpers when they maintain the starting position.

The horizontal displacement of the BMC in the sagittal plane during push-off was found to be similar between the two groups. The difference in BMC position found between the two age groups when maintaining the starting position was therefore preserved at takeoff. Results showed that the BMC lies above the metatarsophalangeal joint at takeoff in young jumpers. By contrast, in the elderly the line of gravity falls behind the foot center of rotation when taking off from the ground. This position of BMC can be explained by the inability of the elderly to reach a nearly vertical position at takeoff. Results indeed showed that the elderly left the ground in a more flexed position than younger participants.

The flexed position of the elderly at takeoff is not attributable to a premature takeoff since they had already reached their final angular position before the instant of takeoff. Because of the lower joint linear velocities in elderly participants, the simultaneous pattern of joint coordination did not cause a premature takeoff, which is usually associated with high joint linear velocities (Bobbert & Van Soest, 2001). As stated previously, the low joint linear velocities are likely attributable to a lack of explosive force in the extensor muscles with aging. More precisely, we hypothesize that plantar flexors suffer more from a loss of explosive force than do hip and knee extensor muscles. Indeed, a longer delay between the beginning of knee and ankle extensions was found in the older men. This late ankle extension would be due to the incapacity of plantar flexors to generate a high level of force sufficiently early in the push-off. This remains a working hypothesis that will be verified in a future experimental study where joint kinetics as well as muscle activation patterns will be assessed.

Although plantar flexion was delayed relative to the start of knee extension, the peak relative linear velocities of the three lower limb joints occurred simultaneously in the elderly. It can be supposed that the absence of a temporal delay between the peak linear velocities is related to an augmented rigidity of the multijoint system with aging. Previous research has provided inconsistent results on the influence of aging on the coactivation level (Klein, Rice, & Marsh, 2001; Ochala, Lambertz, Pousson, Goubel, & Van Hoecke, 2004). A higher cocontraction level at the ankle has recently been identified as a strategy used by the elderly to deal with disturbance of the standing posture (Benjuya, Melzer, & Kaplanski, 2004). The goal of a postural task differs from that of an explosive multijoint task such as a squat jump. In the first task the goal is to reduce the motion of the BMC, while in the second task the objective is to maximize the BMC vertical velocity. Nevertheless, it is possible that the increased rigidity of the system observed in the present study could come from a general increase in cocontraction level at the lower limb joints. It would take a study using electromyographic recordings to verify this hypothesis.
In conclusion, this study contributes to the understanding of the influence of aging on short duration multijoint movements. Although the elderly do not perform maximal jumps on a daily basis, jumping is a basic movement that is often used in exercise programs for the elderly and which can be used in daily life, for example to avoid obstacles. It is apparent from the present results that the jumping movement and joint coordination are reorganized mainly because of a loss of isometric and explosive force with aging. Jump performance decreased with aging. The sequential pattern of joint coordination commonly observed in young adults is not demonstrated in older adults. The elderly in this study exhibited a simultaneous pattern. This may indicate that adults adjust their pattern of joint coordination as they age. It would be interesting to study whether training the system would improve jump performance in the elderly.

References


