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ORIGINAL ARTICLE

Explosive movement in the older men: analysis and comparative study of vertical jump

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Abstract

Background Loss of power has been demonstrated to have severe functional consequences to perform physical daily living tasks in old age.

Purpose This study aimed to assess how moment and velocity were affected for each joint of the lower limbs during squat jumping for older men in comparison with young adults.

Methods Twenty-one healthy older men (74.5 ± 4.6 years) and 22 young men (21.8 ± 2.8 years) performed maximal squat jumps. Inverse dynamics procedure was used to compute the net joint power, moment and velocity produced at the hip, knee and ankle joints.

Results and discussion Vertical jump height of the elderly was 64 % lower than the young adults. The maximal power of the body mass center ($P_{\max}^{\mathrm{bmc}}$) was 57 % lower in the older population. For the instant at $P_{\max}^{\mathrm{bmc}}$, the vertical ground reaction force and the vertical velocity of the body mass center were 26 % and 35 % less in the older adults than in the young adults, respectively ($p < 0.05$; ES = −1.64 for vertical ground reaction force; $p < 0.05$; ES = −1.10). A lower value of the hip (−60 %), knee (−72 %) and ankle (−68 %) joint powers was observed in older adults. This was explained by both lower values of joint moments (−64, −57 and −61 % for the hip, knee and ankle, respectively) and angular velocities (−59, −49 and −52 % for the hip, knee and ankle, respectively).

Conclusion This study showed a lower joint power when performing vertical jump. This smaller power resulted from both a lower moment and angular velocity produced at each joint.

Keywords Power · Aging · Squat jump · Angular velocity · Moment

Introduction

The age-related decline in physical performance of healthy older people is the consequence of the deterioration of muscle contractile properties due to the aging process [1], and of a progressive reduction of physical activity [2]. More specifically, some studies observed that explosive power output declines with aging [3, 4] meaning that the ability to develop both dynamic strength and speed was impaired [4]. This loss of power has been demonstrated to have severe functional consequences to perform physical tasks of everyday life in old age [5, 6], such as rising from a chair [7], climbing stairs [8] or even the prevention of fall and trips [9]. In the literature, investigations looking at muscle power in older people are not as numerous as those carried out on muscle strength [10]. Therefore, improved knowledge on the mechanisms of power decline is crucial with regard to the development of effective prevention and treatment programs for preserving mobility and independence in older people [2].

A simple way to assess power capacity is to analyze a standardized movement such as maximal vertical jumping. Indeed, the mechanical power is highly correlated with vertical jump performance [11, 12]. Although the biomechanical characteristics of this type of jump have been the

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topic of numerous works in young populations [13–16], the effects of aging on mechanical power during vertical jumping remain less studied [17–19]. Most of the studies observed an impaired performance with aging measured through vertical jump height [16, 20]. In addition, De Vito et al. [21] reported a smaller average and maximal power of the lower limbs during vertical jumping in older adults. Thereby, jump test variables, such jump power, were found to be useful for sarcopenia screening [16] and functional status [22]. In order to better understand the power impairment, several studies focused on age-related changes in contraction velocity [23, 24]. Especially, Macaluso and De Vito [24] indicated that velocity was the critical determinant of the age-related decline in power in healthy older women. Therefore, some studies were interested in high-speed resistance training to increase functional capacity and muscle performance in olders [25, 26]. However, to the best of our knowledge, no study focused on the cause of power impairment (i.e., joint moment and velocity impairment) in healthy older male. The results may be different from women [16, 27] whose muscle power is often lower than men [5, 28]. It may be relevant to better understand the cause of power impairment in older male, in order to improve prevention and treatment programs.

Therefore, the present study aimed to assess how moment and velocity were affected for each joint of the lower limbs during squat jumping for older men in comparison with young adults. It was hypothesized that decline in lower limbs power during vertical jumping was explained by both a lower moment production and angular velocity.

Methods

Participants

Twenty-one healthy and physically active older men (mean ± standard deviation, age = 74.5 ± 4.6 years; height = 1.70 ± 0.05 m; mass = 79.2 ± 10.2 kg) and eighteen healthy athletic young males (age = 21.85 ± 2.8 years; height = 1.78 ± 0.05 m; mass = 69.86 ± 8.95 kg) volunteered to take part in this study. The experimental tests were approved by French Ethics Committee Sud Est II, and all the participants signed an informed consent after reading the procedure details.

In order to differentiate the two groups, some inclusion criteria were taken into consideration. The older participants required to be over 65 years old [29]. All of them actively participated in structured group exercise or individual physical activity or sport; throughout the week, they had to engage in at least 150 min of moderate-intensity aerobic physical activity, or at least 75 min of vigorous-intensity aerobic physical activity, or an equivalent combination of moderate- and vigorous-intensity activity, determined by a validated Physical Activity Questionnaire [30, 31]. Furthermore, the older adults completed a medical questionnaire to confirm the absence of severe cardiopulmonary and neurological impairments, balance disorders or recent musculoskeletal troubles. Finally, the passive range of motion of the ankle, knee and hip joints was measured in order to ensure the absence of pathological joint mobility [32]. The young participants had to be between 18 and 30 years old; none of them presented recent or current musculoskeletal troubles.

Study design and procedure

Prior to the experimental protocol, a 5-min warm-up session on a cyclo-ergometer (Ergometer X7, Kettler, Germany) was performed. Participants also trained to perform sub-maximal and maximal vertical squat jump (SJ) from a preferred initial posture, in order to be familiarized with the experimental test. The training session was necessary, especially for the older participant, to minimize a possible unbalance during the push-off phase or apprehension caused by the landing phase. The test consisted in performing 3 maximal SJs with a 3-min rest interval between each test in order to avoid the effect of fatigue. The participants were instructed to jump as high as possible without any preparatory countermovement and to keep their hands on their hips. Moreover, to determine the start of the push-off (offline), the participants were asked to maintain their initial squat posture for 1 s before starting to jump. Offline, individual ground reaction force traces were analyzed to verify whether a countermovement had occurred, in which case the trial was deleted.

Instrumentation and data acquisition

Participants were filmed in the sagittal plane using a 100-Hz camcorder (Ueye, IDS UI-2220SE-M-GL). Reflective markers were placed on the skin on the left fifth metatarsophalangeal, lateral malleolus, lateral femoral epicondyle, greater trochanter and acromion [33]. Three-dimensional components of the ground reaction force and center of pressure were recorded with a single force platform (AMTI force plate model OR6-7-2000) sampled at 1200 Hz.

Data treatment

The kinetic data were smoothed with a zero-lag fourth-order low-pass Butterworth filter with a cutoff frequency of 15 Hz and downsampled to 100 Hz. For each trial, the
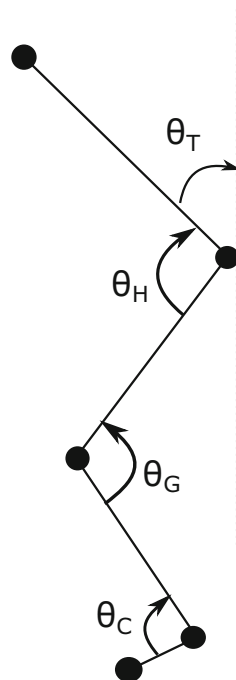
mean and standard deviation of the vertical ground reaction force (R_z) were determined over the first second in which the participants maintained the initial equilibrium posture. The beginning of the push-off corresponded to the instant, when after the first second, the vertical ground reaction force increased more than 2 standard deviations above the body weight (method adapted from Vanrenterghem et al. [34]). Then, the kinematic and kinetic data were synchronized. To that aim, the end of the push-off was determined for kinematics and kinetics. It corresponded, respectively, to the last frame when the feet were in contact with the ground and the last time value before R_z dropped to zero.

Marker positions were digitized frame by frame with an auto-recognition software developed by the Museum National d'Histoire Naturelle (Paris, France) and already used for vertical jumping [35, 36]. The raw coordinates of the markers were smoothed with a zero-lag fourth-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Consequently, the participants were modeled in the sagittal plane by 4 rigid segments composed of the feet, the lower legs, the upper legs and the segment "Head–Arm–Trunk" (HAT) (Fig. 1). For the lower limb segments, the right and left sides were grouped together.

Kinematics

The location of each segment center of mass was determined using anthropometric data from Winter [37]. Then, using the relative segmental mass [37], the body mass center (BMC) position was computed. The vertical jump height (Δh_{flight}) was defined as the height reached by the

BMC at the apex of the jump, relative to the height of the BMC at takeoff according to Vanrenterghem et al. [34] (Fig. 2). The jump with the highest Δh_{flight} value was selected for further analysis.

Kinetics

The net joint moments were calculated with a standard inverse dynamic (bottom-up) procedure based on ground reaction force/moment and kinematic data [37]. Net joint moments were defined positive with joint extension. Joint power was computed as the product of the net joint moment and angular velocity. At maximal joint power, the values of the joint moment and the angular joint velocity were reported. The global power ($P_{\text{max}}^{\text{bmc}}$) was calculated as the product of the vertical ground reaction force and vertical velocity of BMC. For the instant at $P_{\text{max}}^{\text{bmc}}$, the values of R_z and BMC vertical velocity were described. The rate of force development (RFD) was calculated as the difference between R_z peak and R_z at the first instant of the push-off phase divided to the time taken to achieve R_z peak. Finally, all kinetic variables were normalized with respect to the participant body mass.

Statistical analysis

Statistical analyses were conducted using the R distribution free software (R.2.7.2., R Foundation for Statistical Computing, Vienna, Austria). To compare previous cited variables between young and older participants, independent sample Student t test was used. The significance level was set at $p < 0.05$. For substantive significance, effect sizes (ES) were reported. Values would be compared to the conventional sizes (small = 0.2, medium = 0.5, large = 0.8) following the lines of Cohen [38].
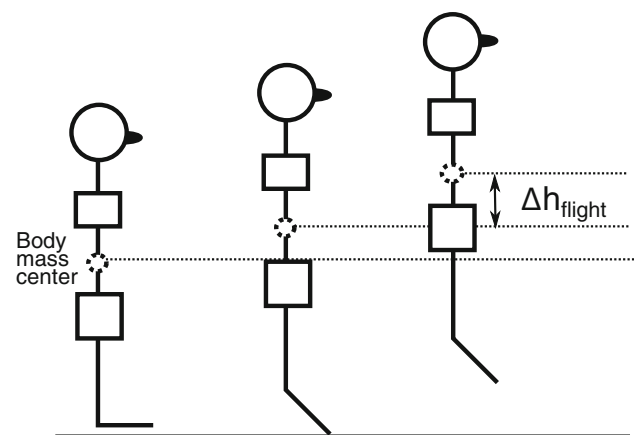

Fig. 1 Definition of the hip (θ_H), knee (θ_K) and ankle (θ_A) angles and segments of the model

Fig. 2 Sketch of discrete variables describing general characteristics of the standing vertical jump

Table 1 Elderly and young kinematic and kinetic variables during a squat jump

Variables	Elderly		Young		p value
	Mean	SD	Mean	SD	
Δh_{flight} (m)	0.13	0.05	0.36	0.11	<0.0001
Push-off duration (s)	0.467	0.11	0.376	0.07	<0.0013
P_{max} (W kg^{-1})	27.81	7.65	65.36	31.16	<0.0001
R_{z} (N kg^{-1}) at P_{max}	15.32	1.34	23.54	1.20	<0.0001
BMC vertical velocity at P_{max} (m s^{-1})	1.81	0.35	2.77	0.87	<0.0002
RFD (N s^{-1})	2535	1640	5683	2922	<0.05

Δh_{flight} vertical jump height, P_{max} maximal power, R_{z} vertical ground reaction force, BMC body mass center, RFD rate of force development

Results

Selected kinematic and kinetic parameters for both the older and the young groups are presented in Table 1. The older adults had a 0.23 m lower jump height (Δh_{flight}, $p < 0.0001$; ES = −2.18) than the young. The total duration of the push-off phase was on average 0.91 s (+26 %) longer in older than in younger men ($p < 0.0001$; ES = 1.3). The RFD and $P_{\text{max}}^{\text{bmc}}$ were 55 and 57 % less in the older adults than in the young group ($p < 0.0001$; ES = −0.92; $p < 0.0001$; ES = −1.2, for RFD and $P_{\text{max}}^{\text{bmc}}$, respectively). For the instant at $P_{\text{max}}^{\text{bmc}}$, the values of R_{z} and BMC vertical velocity were 26 and 35 % less in the older in comparison with the young ones ($p < 0.0001$; ES = −6.46 for R_{z}; $p < 0.0001$; ES = −1.10 for BMC vertical velocity).

Selected joint angle parameters during the push-off phase are presented in Table 2. Initial and final angles of the hip, knee, and ankle joints were not statistically different between the groups. Moreover, forward trunk inclination was not statistically different between the two populations for the initial position of the push-off phase ($p > 0.05$; ES = −0.21) (0.75 ± 0.29 rad vs. 0.69 ± 0.22 rad, for older and young, respectively).

In comparison with the younger population, a significant decline of 14.73, 11.59 and 30.04 W kg^{-1} for the hip, knee, and ankle maximal net joint powers ($p < 0.001$; ES = −2.33; $p < 0.001$; ES = −1.55; $p < 0.001$; ES = −2.76, respectively) was observed in the older population.

The values of joint moment and angular joint velocity at maximal power for each lower limb joint are reported in Table 3. For all joints, from hip to ankle, we noted that joint moment ($p < 0.05$; ES = −1.23; $p < 0.05$; ES = −1.25; $p < 0.05$; ES = −1.93, respectively) and angular velocity ($p < 0.05$, ES = −2.14; $p < 0.05$, ES = −1.72; $p < 0.05$, ES = −4.82, respectively) were statistically lower for the older adults than the young.

Table 2 Angle (θ) values, at initial ($t = 0$) and takeoff, of the hip (H), knee (K) and ankle (A) joints for elderly and young groups

Variables	Elderly		Young		p value
	Mean	SD	Mean	SD	
At $t = 0$					
θ_{H} (rad)	1.55	0.29	1.33	0.34	0.36
θ_{K} (rad)	1.62	0.19	1.74	0.21	0.11
θ_{A} (rad)	1.56	0.11	1.56	0.12	0.98
At takeoff					
θ_{H} (rad)	2.78	0.14	2.7	0.17	0.20
θ_{K} (rad)	2.81	0.10	2.77	0.09	0.23
θ_{A} (rad)	2.32	0.11	2.38	0.07	0.80

Discussion

This study aimed to analyze the age-related decline in power, with the main purpose of determining which part of joint velocity or joint torque was affected during squat jumping. For this purpose, this work focuses on the comparative analyses of the peak powers, moments and angular velocities for each joint of the lower limb in young and older males.

Our study showed a lower maximum performance among seniors compared to the younger population, with a significant drop in jump height (−64 %). Our results agree with those reported in the literature, which show a reduction ranging from 22 to 65 % in vertical jump height between populations aged of 22 and 70 years [19, 39, 40].

The execution of an explosive movement such as the squat jump is also characterized by a strong temporal constraint with the need to quickly generate a large force to takeoff. However, time required to produce maximum power increases with age [4] and this parameter seems to be deteriorating even faster than the decrease in force during aging [41]. In our study, the RFD was thus two times lower in the elderly population. However in spite of a

Table 3 Elderly and young angular velocity and moment at peak power in the hip, knee and ankle joints (mean ± SD)

Variables	Joint	Elderly		Young	
		Mean	SD	Mean	SD
Peak net joint power, ($P_{peak\ joint}$) W kg^{-1}	Hip	9.86	6.6	24.58	6.4
	Knee	4.49	2.1	16.08	7.5
	Ankle	14.11	3.8	44.15	11
Net joint moment at P_{peak}, N m kg^{-1}	Hip	1.95	0.6	3.05	0.9
	Knee	1.05	0.4	1.83	0.6
	Ankle	1.96	0.3	3.22	0.7
Angular velocity at P_{peak}, rad s^{-1}	Hip	4.91	1.9	8.28	1.6
	Knee	4.34	1.6	8.87	2.6
	Ankle	7.13	1.3	13.64	1.4

All comparisons are significant at $p < 0.0001$

26 % increase in time of the push-off phase, the peak power was reduced by 53 % and was only reached 16 % later compared to the younger population. It has been shown that the RFD is influenced by the intrinsic contractile properties of the muscle (typology, stiffness, fiber pennation angle) and by neuromuscular properties [42]. The increased atrophy of fast fibers compared to slow fibers [43] and the reduction of muscle activation frequency observed in the elderly could explain these results. Moreover, the complexity of a multi-joint movement compared to that of an extension of the knee, for example, most likely accentuates this deficit [44]. The RFD indeed depends on the subject's ability to produce a maximum level of muscular activation regardless of the movement and over a limited period of time.

Besides, a substantial fall (57 %) of P_{max}^{bmc} during the jump was observed in seniors compared to younger subjects. This P_{max}^{bmc} impairment was explained by both a lower value of BMC vertical velocity (−35 %) and R_z (−26 %). This result was in accordance with the literature data relating to a population of physically active seniors [42, 45]. In our study, we identified that P_{max}^{bmc} was equal to 27.81 W kg^{-1} in the older adults, and this was greater than the values (23.1 W kg^{-1}) obtained in the study of Caserotti [46] or De Vito [21] (21.2 W kg^{-1}). This variation can be explained firstly by the difference in gender (men vs. women) [24]. Secondly, we measured the mechanical parameters in a population with aging described as "optimal," for whom the level of activity was close to the standards defined by the WHO (i.e., 150 min of endurance activity at moderate intensity or at least 75 min of endurance activity at a sustained intensity/week). By contrast, Caserotti et al. [46] were interested in studying a sedentary older population ("no participation in regular physical activity"). Furthermore, it would appear that daily physical activities, although far from explosive movements, attenuate the effects of aging on power generation [47].

If a deficit of the global power has been shown, a detailed analysis may enable to identify its implicit mechanisms. Lower hip (−60 %), knee (−72 %) and ankle (−68 %) joint powers were observed in older adults. Our results seemed to confirm the outcomes observed during high-intensity locomotion [48]. Indeed, the most prominent decline in joint kinetics in older age has been shown to occur at the ankle joint level during both running [49] and sprinting [50–53]. The lower joint maximal power was explained by both a smaller net joint moment and angular velocity. A particularly novel aspect of the present findings was that a similar alteration in torque production and shortening velocity was observed (on average −60 and −53 % for the joint moment and velocity, respectively). For dynamic contractions, conflicting reports suggest that angular velocity in older adults is more [43, 54], similarly [55] or less [56] affected than joint moment when compared with younger adults. Because of the inconsistencies among protocols, it is difficult to draw conclusions based upon the equivocal results presented in the literature.

Nevertheless, we may explain this similar alteration literature by several factors. Firstly, in our study, we did not iterate jump tests, which did not alter the angular velocity under the effect of fatigue [57].

Secondly, the high level of activity of the population of our study probably decreases the differences especially on the decrease in the muscle qualities of speed and strength. However, our results corroborate with those of the literature review by Raj et al. [42] who observed a similar loss of strength and angular velocity between the seventh and eighth decades.

These lower vertical jump height and power were observed in spite of the absence of change in joint position values, which is an important variable to consider when assessing dynamic muscle performance [58]. Indeed, the initial and final angles of the hip, knee and ankle joints, on the one hand, and the flexion of the trunk at the initiation of

the impulse, on the other hand, presented similar values between the two groups of participants. These results contrast with those observed during jumping [17, 59] and downward stepping [60] in older adults. These authors highlight a major reduction in the amplitudes of all lower limb joints during the SJ (21 % for hip, 7–11 % for knee and 14–33 % for ankle) and a greater extension of the hip at the initiation of the jump (+7° extension). The author suggested that older tend to stiffen legs and trunk in compensation of impaired neuromotor functions and decreased muscle strength to increase stability [17]. Although not measured, we may speculate that a higher co-activation of the antagonist muscles in older persons can improve joint stability as a compensation for age-related muscle weakness [61], and on the other hand, it will counteract and lower the net force exerted by the agonist muscles [62]. The observation of a high peak power compared to the literature and the invariability of angular positions between our 2 studied groups may support the idea of a small co-activation. The effects could be induced by the preservation of a physical activity on voluntary muscle activation and antagonist muscles co-activation in older persons [47, 61].

Study limitations

When interpreting the results of this study, the constraints of our cross-sectional research design must be considered. Indeed, we must consider carefully the observed values of velocity and strength which are the comparison between distinct young and old populations at a single point in times of aging process. Few studies have taken a developmental approach to aging due to content of difficulty linked to subjects observation time and comparison of a more limited number of variables [49, 63, 64]. Another limitation was that the lower power observed in older adults can be consider only with the load corresponding to their body weight which may represent a high percentage of their maximum strength. Consequently, older population may have not developed their optimal power during vertical jump. Finally, the kinetic data have not been standardized to the lower limb muscle mass of the subjects. Nevertheless, kinetic data were normalized to the body mass of our participants, according to previous studies investigating vertical jumping [15, 17, 36].

Conclusion

This study showed a lower joint power when performing vertical jump in older men. This smaller power resulted from both a lower moment and angular velocity produced at each joint. This finding suggests that it may be important to limit both velocity and strength impairment in order to limit power loss in explosive movement in older population. Considering that most of daily actions require the development of power (e.g., rising from a chair, climbing stairs or even the prevention of fall and trips), our results may reinforce the assumption that a high-speed resistant training program should be included in elderly population. From a practical point of view, a highly constrained multi-joint movement such as vertical jump, mechanography or leg multi-joint movements should be considered for designing appropriate training programs in older adults.

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