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Vertical Stiffness, Jumps and Sprint Kinematics of Well-Trained Youth Female and Male Sprinters

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ABSTRACT

Maximal sprint speed and kinematic step characteristics depend on the vertical stiffness (K_{vert}) and jump strength, which are tested by vertical jumps with short (hopping jump (HT), drop jump (DJ)) and long (counter movement jump (CMJ)) stretch shortening cycle. The purpose was to determine the reproducibility of a HT, and the differences of sprint speed, K_{vert} as well as DJ and CMJ height between groups. Male junior national squad, male and female Hamburger regional squad athletes were measured in flying 30 m sprint and vertical jumps. The group differences were tested with an analysis of variance. The HT (2.2 Hz) reached a high reproducibility with ICC values >0.97 for K_{vert}. The group of the faster male sprinter demonstrated a shorter contact time, higher frequency with comparable flight time during sprint, a higher K_{vert} during HT as well as a higher jump height during DJ, but only a jump height difference of 3 cm during CMJ. The female sprinters realized a lower K_{vert} as the male athletes. Differences of K_{vert} could be tested reliable by means of HT. K_{vert} and the DJ height differentiated between the male groups with different sprint speed (10.04 vs. 9.19 m/s), but not the CMJ height.

Key Words: *Hopping, Maximal sprint speed, Drop jump, Counter movement jump*

INTRODUCTION

During 100-m-run the maximal sprint speed dependent on performance level will be reached between 50-60 or 60-80 m after start (17) and is often tested in training with flying 30 m sprints from an individual run-up out of approximately 5 m. At a middle and high performance level the step length represents the main factor for the maximal sprint speed production (14, 16). Racing analysis shows, that the step frequency reaches already its maximum at 10-20 m after start (10) and further increase of sprint speed is determined through an increase of step length (17). Moreover, the maximal sprint speed is connected to short contact times up to below 100 ms and is thus essentially dependent on the performance in the fast stretch shortening cycle that is a fast transition from eccentric to concentric muscle contraction.

The maximal sprint speed and its kinematic step characteristics is depending on different athletic factors of the lower extremity and of the stiffness, which are often proved by the means of vertical jump tests counter movement jump (CMJ), drop jump (DJ) and rebound jumps. The goal of the CMJ is to reach a maximal height with a long contact time from more than 200 ms. The contact time at DJ vary between 120 to 180 ms dependent on the jump altitude (30). In hopping test (2.2 Hz) there are contact times for non-professional player encountered in the range of 175 ms (7, 24).

With vertical, leg and joint stiffness different forms of lower extremity stiffness can be distinguished (5). The vertical stiffness describes the ratio between maximal vertical ground reaction force and vertical center of mass displacement. The calculation of the vertical stiffness is effected by means of the spring mass system (7). The output value for the stiffness calculation is determined by different methods of measurement (force platforms, contact mats or light barriers). Furthermore, different methods for stiffness calculation probably affect the results (6).

The leg or vertical stiffness measured during hopping test depends on hopping frequency, surface, shoes, gender, performance level, athletic specialization and can be modified by training. Hopping tests are realized with defined or different frequencies (13, 24), because the stiffness increases with increasing hopping frequency (8, 9). An early study demonstrates that while jumping at place a preferred frequency from 2.2 Hops/s will be chosen. At this frequency the body behaves like a simple spring-mass system (8). This finding was essential for the determination of the hopping frequency in later tests. An earlier study confirmed this result, since lower leg stiffness appeared at a hopping frequency less than 2 Hz both in maximal and submaximal jump height than with 2.2 Hz (24).

The leg stiffness depends on the surface and the properties of the shoes. At a soft elastic surface, a low stiffness will be determined and vice versa (23). Since the hopping test, accomplished barefooted vs. with cushioned shoe conditions, leads to a divergent stiffness (2), the hopping test should be accomplished barefooted to exclude the shoe's interfering impact. Studies according to leg stiffness of female and male athletes demonstrate consistently higher leg stiffness of the male athletes both in hopping test (2.2 Hz) (1) and with three hopping frequencies, 3.0, 2.5 Hz, and a preferred hopping frequency (10) as well as during double-legged drop landings with changes in drop height from 40 – 60 cm (29). Leg and vertical Stiffness differences were observed for elite and intermediate female and male sprinter as a function of skill and gender (22). In contrast, a study suggests no gender differences in leg stiffness at three different hopping frequencies (13).

For male sprinter with a mean 100 m time from 11.43 s a leg stiffness of hopping test as a predictor for sprint speed in the phases from 30 – 60 m and 60 – 100m has been shown (4). For 16 years old handball players the leg stiffness (2 Hz) correlated with the maximal sprint velocity (7).

Investigation according to the connection of CMJ and/or DJ with sprint speed for sprinters yields inconsistent findings (15, 18). On the one hand it is reported about a stronger correlation between DJ (50 cm) and maximal sprint speed in comparison to CMJ (21). On the other hand, a correlation of the maximal sprint speed and the CMJ height for male and female sprinter as well as athletes, who performed the CMJ and the DJ out of different drop heights (30, 45, 60, 75 cm), were found, but not for the reactive strength index of the DJ (30). A further study investigated the maximum running velocity, the CMJ and the DJ from heights of 30, 50 and 80 cm for trained male sprinter and presented that coherence exists between the sprint speed and the DJ from a height of 30 cm (3).

In contrast, a coherence between CMJ and the 30-m, 100-m and 300-m sprint times were ascertained, but not for the DJ (12). Likewise, for male sprinters, who completed different jump tests (CMJ, DJ, repeated jump) and a 100-m sprint, the squat jump or the CMJ presented the best predictor for the 100 m performance and the DJ height correlated only with the speed of 0 – 10 m (28). In addition, the jump height and the ground reaction force of the CMJ correlated with the 100 m performance (4), with the 60-m sprint performance (18) as well as the maximal sprint speed during 30 m and 50 m (15). Higher levels of lower-body stiffness also facilitate performances in other sports during movement with iterative stretch shortening cycle (25). Long and triple jumper with plyometric training background exhibit higher leg stiffness in contrast to the control group (26). Resistance trained athletes have a higher leg stiffness than distance runner (12). Distance runner and gymnasts presented higher stiffness than the control group (27).

In summary, despite frequent investigations of sprints and vertical jumps, findings according to the production of the sprint speed, vertical stiffness, DJ and CMJ in comparison to junior athletes with different sex and performance levels are left. Therefore, the purpose of this study was (1) the determination of the relative and absolute reproducibility of the hopping test with 2.2 Hz and (2) to compare the sprint and jump data of junior athletes with different sex and performance level.

With that it was expected, that in accordance to the gender and the sprint ability the vertical stiffness is distinguished from the data of CMJ and DJ, whereas the more powerful sprinter and the male sprinter demonstrate the higher values in comparison to the female athletes.

MATERIAL AND METHODS

Participants

A priori sample size calculation (G*power 3.1., ANOVA (one way); f= .59; α= .05; power= .80, number of groups= 3) calculated a total number of 33 participants. The field investigation took place in an athletic sports hall at two different locations in Berlin and Hamburg. Voluntary sprinter with three different performance levels participated in this investigation (Table 1). The junior national squad athletes were in average one year older than the Hamburger reginal squad athletes, but have a comparable body mass, body height and leg length. The same aged male Hamburger regional squad athletes were in average 15 kg heavier and 16 cm taller than the female Hamburger regional squad. A few national squad athletes participate successfully in the U18 European championship 2016 over 100 m, 200 m and 4 x 100 m relay.

Table 1
Investigation sample average ± standard deviation for national junior squad athletes (JNS), male (HDSm) and female (HDSf) Hamburger regional squad athletes, N=34.

Sample	Test Location	Age [years]	Body Mass [kg]	Body Height [cm]	Leg Length [m]
JNS, n=12	Berlin	17.8 ± 0.7	75.1 ± 9.4	1.85 ± 0.08	96.3 ± 4.2
HDSm, n=7	HH	16.6 ± 1.4	75.7 ± 12.8	1.86 ± 0.08	95.8 ± 5.3
HDSf, n=15	HH	16.5 ± 2.8	60.6 ± 7.7	1.7 ± 0.05	89.6 ± 4.9

The test procedures were in accordance with the Helsinki Declaration of 1975. Data collection was a part of measurements in routine sport science support in agreement with the track and field association of Hamburg (Hamburger Leichtathletik Verband, HHLV) and the German Athletics Association (DLV). Before investigation the subjects were informed about the tests and agree voluntary with an informed consent.

Test Procedure

After the general warm-up phase a specific sprint warm-up followed. Then athletes performed two maximal 30 m flying sprints with a break of minimum 15 minutes between the runs. After this the athletes completed two hopping-tests for determining the vertical stiffness. The hopping-test was performed over 12 s under barefoot conditions with a frequency of 2.2 Hz. The aim for the athletes was to jump as high as possible but with minimal ground contact time. The last 20 jumps were assessed. The break between the two hopping-tests was longer than 5 minutes. In randomized order the CMJ and the DJ followed. The athletes participated in every jump variation three times with a break of more than 5 minutes between each jump. The drop height of the DJ was 40 cm for the male and 30 cm for female athletes. The task for the athletes was to jump as high as possible with short contact time. Der CMJ was accomplished by using an arm swing for reaching a maximal jump height.

Measuring System and Data Analysis

A threefold light barrier (Wilhelm Köster, Ditzingen Germany) registered the 30 m sprint time with a measuring frequency of 1000 Hz. The Optojump Next System (Microgate, Italy) measured the ground contact time and flight time during 30 m flying sprint for every step and all various jumps. The light barriers of the Optojump Next device are located 5 mm above the ground with a distance of 1 cm between each barrier. The measuring frequency was 1000 Hz.

For the sprint the mean sprint speed over 30 m, the mean of step length, step frequency, contact time and flight time for all steps were calculated. The height of all jumps was determined by the flight-time-method. For the DJ and the hopping tests the reactive strength index (RSI) was calculated with the formula RSI = jump height/ground contact time. The vertical stiffness was calculated through the spring mass model. The fastest sprint, the highest CMJ and the jump with the highest RSI (DJ and Hopping) from every subject were analyzed. The vertical stiffness (K_{vert}) computation refers to (20) McMahon and Cheng (1990), Butler (5) with the formula:

$$K_{vert} = F_{max} \cdot dy_c^{-1}$$

F_{max} is the maximal ground reaction force calculated through contact and flight time in considering the body mass of the athlete and dy_c^{-1} describes the vertical displacement of the center of mass.

The two hopping tests were used to determine the reproduction of K_{vert}. The relative reproduction was assessed by means of Intra-Class-Coefficient (ICC=3.1). In addition the standard error of measurement ($SEM = SD \cdot \sqrt{1 - ICC}$) and the coefficient of repeatability ($CR = SEM \cdot \sqrt{2 \cdot 1.96}$) were determined as measurement of the absolute reproduction with ICC and standard deviation (SD).

A single-factor variance analysis with the between-subject factor performance class was calculated in comparison to the sample. The examination for standard distribution and variance homogeneity was calculated by using the Kolmogorov-Smirnov-Test and the Levene-Test. The significance level was determined at $p \leq 0.05$. For all statistic calculations SPSS 21.0 (Chicago, IL, USA) was used.

RESULTS

Table 2 contains the results of the relative and absolute reproducibility of the hopping test. The data shows a high relative reproducibility with ICC values > 0.97 (ICC).

Table 2
Average ± standard deviation as well as data of the relative and absolute reproducibility, the lower (uG) and upper (oG) limit of the confidence interval of ICC (frequency (f), contact time (t_k), flight time (t_f), height (h), reactive strength index (RSI), vertical stiffness (K_{vert})), N=34*.*

Characteristics	Test 1	Test 2	SD	ICC	uG	oG	SEM	CR
f [Hz]	2.204 ± 0.015	2.208 ± 0.011	0.013	0.97	3.322	.102	0.002	0.004
t_k [s]	0.17 ± 0.024	0.17 ± 0.025	0.024	0.986	.970	.994	0.003	0.006
t_f [s]	0.284 ± 0.024	0.284 ± 0.025	0.024	0.977	.950	.990	0.004	0.007
h [cm]	10 ± 1.5	10 ± 1.5	1.5	0.972	.939	.987	0.2	0.5
RSI [m/s]	0.61 ± 0.13	0.61 ± 0.14	0.133	0.973	.940	.987	0.022	0.043
K_{vert} [kN/m]	18.7 ± 4.9	18.8 ± 5	4.90	0.985	.967	.993	0.60	1.19

Table 3 compares the data between the three samples. In sprint test the groups differentiated in sprint speed, contact time, double step length and step length, but not in flight time. The sprint speed was higher for the junior national squad athletes than for the male Hamburger regional squad athletes and the male Hamburger regional squad athletes again achieved higher values than the female Hamburger regional squad athletes. The junior national squad athletes realized shorter contact times and a higher step frequency than the male Hamburger regional squad athletes and the female Hamburger regional squad athletes during comparable flight time. The female Hamburger regional squad athletes sprinted with shorter step length than the two male groups (Table 3).

Table 3

Comparison of the three performance groups (JNS, HDSm and HDSf) of the sprint and vertical jump tests, mean ± standard deviation (sd), 95% confidence interval (CI), contact time (t_k), flight time (t_f), double step length (s_{DS}), double step frequency (f_{DS}), vertical stiffness (K_{vert}), height (h), reactive strength index (RSI), N=34.

Test	data/ sample	JNS		HDSm		HDSf		JNS vs. HDSm	HDSf	HDSf vs. HDSm	main effect
		mean ± sd	CI	mean ± sd	CI	mean ± sd	CI	p-value			
Sprint	v [m/s]	10.04 ± 0.28	9.87-10.22	9.19 ± 0.7	8.54-9.83	8.2 ± 0.38	7.99-8.42	.000	.000	.000	.000
	t_k [ms]	100 ± 7	95-104	123 ± 18	106-139	123 ± 13	116-130	.000	.000	.906	.000
	t_f [ms]	128 ± 10	122-135	124 ± 11	114-135	122 ± 10	117-128	.048	.205	.304	.127
	s_{DS} [m]	4.57 ± 0.25	4.4-4.73	4.52 ± 0.2	4.34-4.71	4.03 ± 0.23	3.9-4.16	.706	.000	.000	.000
	f_{DS} [Hz]	2.2 ± 0.13	2.12-2.28	2.04 ± 0.15	1.89-2.18	2.04 ± 0.11	1.98-2.11	.011	.003	.903	.006
Hopping	K_{vert} [kN/m]	23.8 ± 3.2	21.8-25.8	20 ± 7	13.5-26.5	17.3 ± 4	15.1-19.6	.089	.001	.201	.003
	t_k [ms]	157 ± 9	151-163	178 ± 42	139-217	166 ± 14	158-174	.050	.301	.228	.140
	t_f [ms]	299 ± 10	293-305	277 ± 43	237-317	288 ± 14	280-296	.048	.202	.310	.128
	h [cm]	11 ± 0.7	10.5-11.5	9.6 ± 2.6	7.3-12	10.2 ± 1	9.6-10.7	.047	.135	.401	.110
	RSI [m/s]	0.71 ± 0.09	0.65-0.76	0.59 ± 0.21	0.39-0.78	0.62 ± 0.11	0.56-0.68	.058	.105	.528	.115
DJ	t_k [ms]	170 ± 18	156.8-184.1	181 ± 23	159.3-202.5	169 ± 18	159.2-179.6	.296	.899	.207	.422
	h [cm]	35.3 ± 5.9	30.8-39.8	28.9 ± 8.5	21-36.8	26.1 ± 6.6	22.4-29.8	.076	.004	.379	.013
	RSI [m/s]	2.08 ± 0.12	1.81-2.36	1.63 ± 0.53	1.14-2.11	1.75 ± 0.46	1.3-1.81	.054	.010	.730	.028
CMJ	h [cm]	51.3 ± 5.7	47.2-55.4	48.4 ± 6.2	42.7-54.1	37.6 ± 5.4	34.6-40.6	.308	.000	.000	.000

The vertical stiffness in hopping test differed between the groups, whereas the junior national squad athletes achieved higher values than the male Hamburger regional squad athletes and those again achieved higher values than female Hamburger regional squad athletes. The junior national squad athletes show shorter contact times, longer flight times and a higher reactive strength index than the female Hamburger regional squad athletes. In DJ the jump height and the reactive strength index differ between the groups. Here the junior national squad athletes realized a greater jump height and a higher RSI than the male Hamburger regional squad athletes and the female Hamburger regional squad athletes. In CMJ the jump height of the junior national squad athletes was greater than the jump height of the male Hamburger regional squad athletes and those again achieved a greater jump height than the female Hamburger regional squad athletes.

DISCUSSION

The hopping test achieved for the junior sprinters a high relative reproducibility with ICC values > 0.97 both for the vertical stiffness and its components RSI and contact time. The absolute reproducibility demonstrates the minimal difference, which has to be exceeded when data will be compared, for indicating its practical relevance. For the comparison of the mean values the SEM and for the juxtaposition of the individual data of the athletes the CR could be used. The SEM of the vertical stiffness was 0.6 kN/m. This difference was in comparison to the three samples exceeded distinctively. Thus the vertical stiffness out of the hopping test differentiated between the performance classes and between the gender with higher values for the faster athletes and male athletes in comparison to the female sprinter. Studies with higher leg or vertical stiffness of the male athletes were therefore also verified for junior athletes (1, 22, 29). Observing the postulated hopping frequency (2.2 Hz) did not pose a problem for the subjects. In accordance with former observations (19) there is no need for a familiarization session for the hopping test to preserve reliable test results. Therefore, the hypothetical expected higher vertical stiffness for the faster male sprinter and the higher vertical stiffness of male sprinter in comparison to female sprinter could be verified.

The junior national squad athletes demonstrated, as expected, with 10.4 ± 0.28 m/s a higher sprint speed than the male regional squad athletes with 9.35 ± 0.47 m/s followed by the female reginal squad athletes with 8.2 ± 0.38 m/s. The athletes of the three subsamples varied also according to the chronological age, the body mass and height. The national squad athletes were circa one year older than the Hamburger regional squad athletes. The female sprinter had, as expected, less body weight, body height and leg length. However, the male athletes possessed comparable values at these anthropometric characteristics.

At sprint test, the groups differed even in the contact time, the double step length and the step frequency, but not in flight time. The faster junior national squad athletes achieved strikingly shorter contact times with 100 ± 7 ms than the female and male Hamburger regional squad athletes. The shorter contact time depicts a crucial characteristic of the maximal sprint speed and demands the ability of sprinter to unfold high forces in a short time within the stretch shortening cycle. During a short contact time a vertical force as high as possible has to be generated for a long time and an optimal ratio of horizontal brake and acceleration impulse has to be persisting to maintain the maximum sprint speed.

The short contact time of the faster junior national squad athlete necessitates crucially the higher step frequency and concedes, by tendency, a longer flight time and a greater step length. Although both male samples differentiated conspicuously according to the sprint speed, a significant difference with respect to the step length had not been found. The step length as a main factor for a middle and high performance level (14, 16) was thus in a comparison of the junior athletes not confirmed directly. Moreover, this result seems to be remarkable, because both male groups have a comparable averaged body mass and leg length. Nevertheless, the standard deviation of the body height with 8 cm, the leg length with 4 or 5 cm as well as the step length with 20 or 25 cm was noticeable. The considerable contribution could be ascribed to the group composition, since both male samples combine sprinter of short and long distances. Long distance sprinter are normally taller and have a longer step length than short distance sprinter, but are slightly lower over 30 m flying sprint. The sample composition could possibly cover the impact of the step length to the maximal sprint speed and explain the missing significance.

With the comparison of the female and male Hamburger athletes the gender differences in body height and leg length become efficient, since the male athletes sprint with higher maximal sprint speed due to the greater step length at comparable step frequency, contact and flight time.

The vertical jumps differentiate very well between genders. The male athletes realize a higher vertical stiffness at the hopping test, jump higher at CMJ as well as DJ than the female sprinter. The greater jump height of the male subjects was even having regard to the 10 cm higher jump altitude at DJ (40 vs. 30 cm) expected and confirmed. The gender differences at the hopping test were, however, first evident in the vertical stiffness and not in contact and flight time. Consequently, the less stiffness is determined primarily by the less body mass of the female athletes at comparable contact and flight time, since a less body mass reduce the requirements on the vertical stiffness to realize comparable contact and flight times at the hopping test.

By contrast the data from hopping test and drop jump test differs between the male athletes, but not the jump height from the CMJ. Thereby it should be taken in consideration, that the athletes accomplished the CMJ with a natural arm swing and the DJ as well as the HT without an arm swing. A maximal jump height without any further regimentation was stipulated for the CMJ. Accordingly, the jump height was not only determined conditionally by the jump strength within a long stretch shortening cycle, but also was influenced by the coordination of the arm swing as well as the flexion und extension at the knee and hip joint. The conditions at DJ and hopping test were more strongly controlled by the jump altitude or hopping frequency as well as the demands for minimal contact time and maximal flight time. This led finally to an approximation to the demands of the sprint with reduced contact time, which were at the hopping test with 179 ms (male Hamburger regional squad athletes) in the range of former studies (7, 24) or with 157 ms (junior national squad athletes) and 166 ms (female Hamburger regional squad athletes) shorter.

The results of the male junior athletes verified therefore the expectation of a higher vertical stiffness and test results at the DJ for faster athletes, but the expected jump height differences at the CMJ was not be found. Therefore, the findings corroborate the connection between the reactive strength index and the height of the DJ and the maximal sprint speed (3, 21, 28, 30). An explanation could be found in the sprint performance of the investigated athletes, since the CMJ with long contact time could differ at high performance differences. For 20 male and female sprinter and athletes a correlation of the maximal sprint speed with the CMJ height and the sprint time could be demonstrated, but not with the reactive strength index of the DJ (30). A connection between the CMJ and the sprint time could be determined for seventeen trained female high school competitive sprinters (11), twenty-five male young sprinters with a heterogeneous 100-m-time (10.72-12.87 s) (4), track and field athletes (sprinters, jumpers and throwers) (18) as well as for team sports athletes and non-elite sprinters (15).

The stiffness was calculated by use of the contact and flight time method. A measuring of the maximal ground reaction force through a force platform did not happen. Furthermore, the small sample size and the different number of subjects for each subsample limited the study.

CONCLUSION

The hopping test presents a reliable test procedure for the determination of the vertical stiffness for junior athletes and with that changings in the vertical stiffness in consequence of training could be diagnosed. Junior athletes with higher sprint speed demonstrate higher vertical stiffness at the hopping test and female athletes lower values than male athletes. The faster junior sprinter reaches higher maximal sprint speed due to greater step length and shorter contact times, which determine at a comparable flight time a higher step frequency. Female athletes sprint in contrast to the male athletes with comparable strep frequency shorter steps. At the group comparison the faster male sprinter reaches a higher vertical stiffness and a DJ height at comparable CMJ height. The striking higher sprint speed (10.04 m/s vs. 9.19 m/s) is only confirmed by a slight jump height difference at the CMJ of circa 3 cm.

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