Leg strength and stiffness as ability factors in 100 m sprint running

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Background. The purpose of this study was to determine the importance of leg strength and stiffness relative to i) 100 m sprint performance, ii) mean speed on the three phases of the 100 m race (30-60-100 m) and iii) the speed differences between these phases.

Methods. Nineteen regional to national level male sprinters competed in a 100 m race. Video analysis was used to determine mean velocity parameters. Two subgroups were created since some of the runners decreased their velocity during the third phase (G_2), whereas others maintained or accelerated it (G_3).

Results. The mean performance over 100 m was 11.43 sec (10.72-12.87 sec). The concentric half-squats were related to 100 m (r=0.74, p<0.001) and to the mean speed of each phase (r=0.75, p<0.01). The counter movement jump was related to 100 m (r=0.57, p<0.05) and was the predictor of the first phase (r=0.66, p<0.01). The hopping test was the predictor of the two last phases (r=0.66, p<0.05). Athletes who had the greatest leg stiffness (G_1) produced the highest acceleration between the first and the second phases, and presented a deceleration between the second and the third ones.

Conclusions. The concentric half-squats test was the best predictor in the 100 m sprint. Leg stiffness plays a major role in the second phase.

Key Words: Running - Leg, physiology - Muscle, skeletal, physiology.

The 100 m sprint is usually divided into three phases: i) an acceleration phase; ii) a maximal velocity phase; iii) and a deceleration phase. Each phase seems to correspond to specific abilities. Delecus et al. selectively altered the first and/or the second phases using different types of strength training. Concentric training against high resistances (maximal repetitions against the heaviest possible load) resulted in an improved acceleration phase, while plyometric training (high-velocity training: unloaded exercises) improved the acceleration phase and the maximal velocity phase. The ability to sustain this maximal velocity over the last metres was not modified by either of these two types of training. Similarly, Young et al. showed that the strength qualities were related to the start speed, measured from 0 to 2.5 m, and to the maximum speed, measured over the 10 fastest metres, i.e. 40 to 50 m, during maximum 50 m sprints. In this study, the three phases of the sprint were not considered. To our knowledge, no study has related leg strength with the mean velocity sustained in each of the three phases of a 100 m sprint event.

In any cyclic explosive event, such as sprinting, effi...
This performance was divided into three parts to determine the importance of leg strength and stiffness relative to i) the average speed and stiffness relative to i) the average speed sustained in each phase and ii) the average speed differences between these phases.

### Materials and methods

#### Subjects

Nineteen junior to senior male sprinters, competing at a regional to national level, gave their informed consent to participate in this study. Before giving their written consent, the subjects were fully informed of the nature and the associated risks of the study in agreement with the recommendations of the local Ethics Committee. The mean ± standard deviation (SD) of their physical characteristics and their best performance in time (Trecord) and velocity (Vrecord) are reported in Table I. All the athletes were fully motivated and accustomed to producing maximum efforts during training sessions. The evaluation of the leg strength and stiffness was part of the standard evaluation procedure developed for their training.

#### 100 m in official competition

The 100 m performance taken into account was completed during an outdoor official competition (1997). The performance on 100 m was measured with an electronic timer (accuracy ± 0.001 sec) and the corresponding mean velocity (V100) was determined. All races were video-recorded with two cameras (25 Hz, one frame for around 34 cm) positioned exactly 30 and 60 m from the starting line (at the first level). The cameras recorded the smoke from the starter’s shot gun, before being adjusted perpendicularly to the 30 and 60 m marks positioned on the opposite side of the track (the cameras recorded the athletes only when they crossed the 30 and 60 m lines). Marks placed on the floor and on the opposite side of the track allowed locating the moment when the athlete’s chest crossed the 30 and 60 m lines. These video-recordings were used to divide the races into three phases: i) the first from 0 to 30 m which corresponds to the acceleration phase; ii) the second from 30 to 60 m which represents the maximal velocity phase; iii) and the third from 60 to 100 m which is the deceleration phase. Each phase was characterised by a respective mean

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**Table I.** Physical characteristics and protocol results of the entire group (G) and the subgroups (G1, G2).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>G (n=19)</th>
<th>G1 (n=8)</th>
<th>G2 (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22.3±3.9</td>
<td>22.5±3.9</td>
<td>22.1±4.0</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>72.8±7.6</td>
<td>72.9±8.6</td>
<td>72.8±7.4</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176.2±6.6</td>
<td>176.1±5.5</td>
<td>176.2±7.5</td>
</tr>
<tr>
<td>Trecord (sec)</td>
<td>11.17±0.63</td>
<td>10.92±0.43</td>
<td>11.36±0.71</td>
</tr>
<tr>
<td>Vrecord (m·sec⁻¹)</td>
<td>8.97±0.48</td>
<td>9.17±0.34</td>
<td>8.83±0.53</td>
</tr>
<tr>
<td>V100 (m·sec⁻¹)</td>
<td>8.77±0.44</td>
<td>9.03±0.35</td>
<td>8.58±0.42*</td>
</tr>
<tr>
<td>V1 (m·sec⁻¹)</td>
<td>7.15±0.18</td>
<td>7.27±0.10</td>
<td>7.07±0.18*</td>
</tr>
<tr>
<td>V2 (m·sec⁻¹)</td>
<td>9.55±0.80</td>
<td>10.20±0.51</td>
<td>9.08±0.62***</td>
</tr>
<tr>
<td>V3 (m·sec⁻¹)</td>
<td>9.86±0.65</td>
<td>10.00±0.61</td>
<td>9.75±0.68</td>
</tr>
<tr>
<td>V2.1 (m·sec⁻¹)</td>
<td>2.40±0.69</td>
<td>2.93±0.47</td>
<td>2.01±0.57**</td>
</tr>
<tr>
<td>V3.2 (m·sec⁻¹)</td>
<td>0.30±0.53</td>
<td>-0.20±0.14</td>
<td>0.17±0.39***</td>
</tr>
<tr>
<td>Fmax (N·BW⁻¹)</td>
<td>30.9±3.9</td>
<td>32.5±4.6</td>
<td>29.7±3.1</td>
</tr>
<tr>
<td>hUM (cm)</td>
<td>48.6±3.9</td>
<td>50.3±2.4</td>
<td>47.4±4.3</td>
</tr>
<tr>
<td>K (kN·m⁻¹)</td>
<td>31.4±4.5</td>
<td>34.4±4.1</td>
<td>29.3±3.5**</td>
</tr>
</tbody>
</table>

V100, V1, V2, V3, Vrecord, mean velocities reached during the 100 m race; V100, V1, V2, V3: velocity differences between phases; Fmax, K: neuromuscular qualities. Results are mean±SD (for parameters definitions, refer to the text). G2 significantly different from G1: *p<0.05; **p<0.01; ***p<0.001.
velocity, $V_1$, $V_2$ and $V_3$, determined by the video analysis. These mean running velocities (in m⋅sec$^{-1}$) were expressed by $T_1$, $T_{1+2}$ and $T_{100}$, i.e. the time (in sec) necessary to reach the 30, 60 and 100 m marks on the track. $T_1$ and $T_{1+2}$ (and respectively $V_{1+2}$) were calculated according to the number of frames recorded between the start and the moment when the athlete’s chest crossed the 30 and 60 m lines.

The difference of the velocity (in m⋅sec$^{-1}$) between the second and the first phase ($V_{2-1}$) and between the third and the second ones ($V_{3-2}$) was determined to study the acceleration and/or deceleration. These findings were used to divide the sprinters into two groups. Group 1 ($G_1$) corresponded to the athletes who sustained a higher $V_2$ as compared to $V_3$, and inversely for Group 2 ($G_2$) where $V_3$ was greater than $V_2$.

**System accuracy**

The relative error of velocity ($\Delta v$, in %) was calculated as follows:

$$\Delta v\% = \frac{\Delta d}{d} \times 100\% = \frac{\Delta t}{t} \times 100\% = \Delta d\% + \Delta t\%$$

where $\Delta d$ (the relative errors of the measured displacement, in %) is the absolute error (0.34 m) of the displacement measurement, $\Delta t$ (the relative errors of measured time, in %) is the absolute error (25 Hz: 0.04 sec) of the time measurement, $d$ is the measured displacement (m) and $t$ is the measured time (sec). For the measured displacements (30 and 60 m), the working times were always greater than 4.04 and 6.92 sec for $T_1$ and $T_{1+2}$, respectively. Thus, applying the above equations, the highest errors were: $\Delta d_1=1.13\%$, $\Delta d_{1+2}=0.57\%$, $\Delta t_1=0.99\%$, $\Delta t_{1+2}=0.58\%$, $\Delta v_1=2.12\%$ and $\Delta v_{1+2}=1.14\%$.

**Neuromuscular qualities**

In the month following the 100 m event, the athletes completed three different laboratory tests to determine the leg strength and stiffness.

**Concentric half-squats.**—All lifts were performed on a guided horizontal barbell (Multipower Basic, Panatta Sport, Aprio, Italy) which allowed only vertical movements. Each subject performed two maximal dynamic half-squats with a loaded barbell, ranging from 20 to 160 kg, on his shoulders. The loads were increased by 20 kg increments. At the start of the movement, the knee angle was fixed at 90°. The knee angle was measured with a goniometer to reproduce the same position on each trial. Once the position was determined, mechanical stops were placed below the guided horizontal barbell to preserve this angle.

The subjects applied force as explosively as possible, from a knee angle of 90° to full extension, keeping their chest upright. Thus, subjects took off for the lightest loads. No counter movement was allowed. The barbell was maintained in contact with the shoulders of the subjects throughout the motion. Each trial was followed by a five-min rest period at least. The best trial was kept for the analysis.

The force was calculated from the double time derivation of the load displacement signal, which was recorded by an optical encoder. The displacement signal was measured every 0.75 mm and sampled at 200 Hz. It was stored on a PC computer (482 DX2, 66 MHz) via an electronic interface card equipped with a 12 bit counter (Hewlett Packard, type HCTL-2000, Palo Alto, California, USA), and digitally filtered with a 12 Hz low-pass Butterworth filter with 0 phase lag. For each lift, the average velocity (in m⋅sec$^{-1}$) and the average force (in N) were the mean instantaneous values measured during the contraction. This test allowed the determination of the maximal force ($F_{max}$ in N⋅Bw$^{-1}$) defined as the leg strength developed for the heaviest load lifted by the subject.

**Counter movement jump (CMJ).**—The CMJs were performed on an Ergojump® (Junghans GMBH - Schramberg, BRD). The equipment and the procedure have been described in detail earlier. Briefly, this apparatus consists of a digital timer (accuracy±0.001 sec) connected to a resistive platform. The timer is triggered by the feet of the subject at the moment of release from the platform, and will be stopped at the moment of touch down. Thus, the flight time during the jump is recorded, and allows the determination of the height reached during the CMJ ($h_{CMJ}$ in cm).

The sprinters were instructed to jump as high as possible, keeping their hands on their hips throughout the exercise. They started with a preliminary counter movement (knees bent at 90°). Five jumps were performed, with a five-min rest between two attempts. The recorded value was the mean of the three best jumps. According to Bosco, $h_{CMJ}$ is a way to assess the explosive leg strength.

Investigating both the relationships of the loaded and the unloaded test (concentric half-squat and CMJ,
respectively) with the performances, can be helpful in choosing the most accurate, or the easiest test to do.

**Hopping test.**—A simple method was developed by Dalleau\textsuperscript{12} to measure leg stiffness on Ergojump\textsuperscript{6} (K, in N·m\textsuperscript{-1}). K was calculated from the ground contact time and flight time recorded during series (10 sec) of maximal bounces performed at the preferred frequency. The method for assessing leg stiffness is described in more details in an appendix at the end of the article. The sprinters were instructed to keep their legs as straight as possible, and their hands on their hips. They had to jump as high as possible and stay in contact with the ground as short as possible. This test was performed twice with a five-min rest period. The mean of the two trials was recorded as the leg stiffness value.

**Statistical analysis**

Data are presented as their mean (t) and standard deviation (±SD). Simple linear regressions were used to relate the neuromuscular qualities i) to \( V_{100} \) and ii) to the speed difference appearing between the three phases. Taking into account the link between the different phases of the race (chronological series), multiple regression analyses was used to study the relation-ships between the phases’ velocities (\( V_1 \), \( V_2 \), and \( V_3 \)), and the leg strength and stiffness.

The variance of \( G_1 \) and \( G_2 \) for all the parameters being similar, the t-test was used to compare the different results produced by these two groups. Linear regression models are built and tested for validation, with Pearson’s coefficient of correlation (r) for simple regression or with the multiple correlation coefficient (R) for multiple regression, at the risk 0.05 (p).

**Results**

The results for all the groups are reported in Table I.

**Performances**

The mean performance over 100 m was 11.43±0.60 sec and varied from 10.72 to 12.87 sec, corresponding to average velocities of 9.33 and 7.77 m·sec\textsuperscript{-1}, respectively. This corresponds to 91 and 76% of the present World record (9.79 sec), respectively.

The athletes accelerated similarly in the first phase. During the third phase, some runners decreased their velocity as compared to the second phase. They were included in subgroup \( G_1 \) (n=8). Other runners maintained or accelerated it. They were included in subgroup \( G_2 \) (n=11), (Fig. 1). The mean (±SD) age, body mass, height, best performance in time and velocity and the differences between these two groups are reported in Table I. \( V_1 \), \( V_2 \) and \( V_{100} \) were significantly higher in \( G_1 \) than \( G_2 \) (Table I). Subgroup \( G_1 \) corresponded to the best performers.

**Leg strength**

The force produced during loaded half-squats was linearly related to the barbell velocity in each subject (\( r^2=0.60-0.96 \), p<0.001-0.05). The maximal force (\( F_{\text{max}} \)) was developed for the heaviest load lifted by the subject which corresponded to 127.3±25.13 kg.

The mean values of \( F_{\text{max}} \) and \( h_{\text{CMJ}} \) are reported in Table I. \( F_{\text{max}} \) (Fig. 2) and \( h_{\text{CMJ}} \) (Fig. 3) were significantly related to \( V_{100} \). In the multiple regression analysis, the greatest coefficient of \( F_{\text{max}} \) was obtained when the three phases were all taken into account (R=0.75, p<0.01), (Table II). \( h_{\text{CMJ}} \) was the predictor of the first phase (Table II) with a regression coefficient value of 0.66 (p<0.01). The multiple regression analysis on the three phases, on the two first phases or on the two
Fig. 2.—Relationship between the maximal force \( F_{\text{max}} \) and the mean velocity reached during a 100 m sprint \( V_{100} \).

Fig. 3.—Relationship between the height reached during the counter movement jump \( h_{\text{CMJ}} \) and the mean velocity reached during a 100 m sprint \( V_{100} \).

extreme phases did not give additional information (Table II).

**Leg stiffness**

\( K \) was neither correlated to \( V_{100} \), nor to \( F_{\text{max}} \) or \( h_{\text{CMJ}} \). \( K \) was the predictor of the second and the third phase (Table II), with a multiple regression coefficient value of 0.66 \((p<0.05)\). The same value was obtained when the three phases were taken into account altogether.

**Discussion**

**Evolution of running speed**

All these data have to be restricted to locally ranked athletes since four sprinters completed 100 m in more than 11.00 sec.

This study showed that all the sprinters did not exhibit similar behaviours during the second and the third phase of the 100 m. Some athletes could not maintain their velocity during the third phase. As these athletes demonstrated greater acceleration during the first phase, they were likely to reach their maximal velocity early in the second phase, enabling them to maintain their maximal velocity during the third phase \( (G_1) \). In contrast, other sprinters probably reached their maximal velocity late in the second phase, and could maintain this maximal velocity throughout the third phase \( (G_2) \). Consequently, their average velocity \( V_2 \) was slightly lower than the velocity reached during the third phase. Further investigations using more cameras \( (e.g. \) placed every 10 m) would be needed to determine accurately the distance within which the maximal velocity would be reached in the second phase by the two groups.

**Leg strength**

In this study, the mean sprint velocity \( (V_{100}) \) was related to both the maximal force \( (F_{\text{max}}) \) and the height

<table>
<thead>
<tr>
<th>Phases</th>
<th>( F_{\text{max}} )</th>
<th>( h_{\text{CMJ}} )</th>
<th>( K )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_1 )-( V_3 )</td>
<td>0.75</td>
<td>0.67</td>
<td>0.66</td>
</tr>
<tr>
<td>( V_1 )-( V_2 )</td>
<td>0.71</td>
<td>0.67</td>
<td>0.59</td>
</tr>
<tr>
<td>( V_1 )-( V_3 )</td>
<td>0.73</td>
<td>0.67</td>
<td>0.35</td>
</tr>
<tr>
<td>( V_2 )-( V_3 )</td>
<td>0.72</td>
<td>0.53</td>
<td>0.66</td>
</tr>
<tr>
<td>( V_1 )</td>
<td>0.61</td>
<td><strong>0.66</strong></td>
<td>0.35</td>
</tr>
<tr>
<td>( V_2 )</td>
<td>0.68</td>
<td>0.53</td>
<td>0.58</td>
</tr>
<tr>
<td>( V_3 )</td>
<td>0.68</td>
<td>0.44</td>
<td>0.24</td>
</tr>
</tbody>
</table>
reached during the CMJ ($h_{\text{CMJ}}$). These results under- line the importance of leg strength during a 100 m sprint. The two strength tests highlight different relationships with the performance. $F_{\text{max}}$ was related to the average speed on each phase and $h_{\text{CMJ}}$ was the predictor of the first phase only. During sprint running, the lower limbs have to produce high forces to accelerate and sustain high running speed. This finding is in accordance with the current literature. The CMJ, referred to as “explosive strength” by Bosco, seems to be an indicator of the acceleration phase. $F_{\text{max}}$ is a better indicator of overall performance. This would suggest that CMJ would be the more appropriate test to evaluate the acceleration training sessions, while concentric half-squat test is more accurate in evaluating overall 100 m performance. Coaches and athletes can thus use: i) only a CMJ test which requires less time and effort to manage the training acceleration session or ii) a concentric half-squat test which allows an evaluation of each of the 100 m phases.

Leg stiffness

Leg stiffness is a quality independent from leg strength, since $K$ was related neither to $F_{\text{max}}$ nor to $h_{\text{CMJ}}$. Mero et al. suggested that pre-activation of muscles is needed for increasing muscle stiffness in order to resist great impact forces at the beginning of contact during sprint running. However, $K$ was also not directly related to $V_{100}$, suggesting that the influence of $K$ varies along the race. During the acceleration phase, muscle contraction velocity is low, corresponding to the longest contact phases. This does not necessitate great leg stiffness. In contrast, during the two last phases, the increase in muscle contraction velocity and the shorter contact phases would imply an elevated leg stiffness. The role played by $K$ as a predictor of the two last phases accounts for this influence.

As compared to $G_2$ sprinters, $G_1$ sprinters, demonstrated a better performance on several parameters ($V_{100}, V_1, V_2$), exhibited greater acceleration between the first and the second phases and displayed a deceleration between the second and the third phases. It seems important to study how these differences are related to leg stiffness. Greater leg stiffness was associated with higher $V_2$ as compared to $V_1$. Moreover, greater leg stiffness was associated with higher $V_2$ as compared to $V_3$. The greater leg stiffness of $G_1$ thus corresponds to a better ability to reach a high maximal velocity in the second phase of the 100 m. The greater acceleration presumably results in fatigue, preventing $G_1$ athletes from maintaining their maximal velocity during the third phase. This result is in line with the evolution of running velocity, exhibited by international sprinters. Indeed, the finalists of the 100 m Seoul Olympic Games and Athens World Championships.

Fig. 4.—Relationship between leg stiffness ($K$) and A) the difference of the velocity between the second and the first phases ($V_{2-1}$), B) the difference of the velocity between the third and the second phases ($V_{3-2}$). Group 1 is represented by the open symbols, and Group 2 by the filled symbols.

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began to decelerate between 60 and the 70 m, i.e. during the third phase defined in this study. This observed high leg stiffness value is in accordance with a recent observation by Chelly et al., 8 that high leg stiffness may be needed for the high running speeds measured over 40 m. Nevertheless, this study was done on handball players, who show substantial sprinting capacity, but are not specialized in sprint performance. Moreover, the relations obtained by these authors were not obtained during competitive conditions.

Conclusions

The results obtained with a group of regional to national level sprinters indicate that maximal leg strength, determined using squatting exercise, is related to the mean velocity sustained in each phase. This underlines the need of producing great force to complete initial acceleration, to reach a high maximal velocity and to manage it. The relation obtained between the height reached during a counter movement jump test and the first phase of the sprint, accounts for the explosive leg strength needed during the initial part of the run. Finally, leg stiffness plays a major role during the second phase. It can be explored easily by a hopping test.

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References


Appendix

The stiffness (K, in N.m⁻¹) calculations are based on modelling of the ground reaction force by a sinus curve:

\[ F(t) = F_{max} \cdot \sin\left(\frac{\pi}{T_c} \cdot t\right) \]\n
where \( F_{max} \) is defined as the peak force value, \( T_c \) is the contact time and corresponds to the half period of the sinus. Assuming that the area under the sinus curve was equal to the impulse of ground reaction force, the peak force, the vertical displacement and the stiffness can be determined.

Determination of \( F_{max} \):

The momentum change during the contact time is equal to:

\[ J_0^T_c \left[ F(u)-Mg \right] \, du = M \Delta v = Mg T_v \]

where \( v \) is the vertical velocity, \( M \) is the body mass, \( g \) is gravitational acceleration and \( T_c \) is the contact time.

Substituting [1] in this equation gives

\[ J_0^T_c \left[ F_{max} \cdot \sin\left(\frac{\pi}{T_c} \cdot u\right) - Mg \right] \, du = M \Delta v = Mg T_v \]
Resolving this equation, the peak force is then:

\[ F_{\text{max}} = Mg \cdot \frac{\pi}{2} \cdot \left[ \frac{T_v}{T_c} + 1 \right] \]  

[2]

**Calculation of the velocity:**

By integration of the vertical acceleration of the body, the velocity is:

\[ v(t) = \int_0^t \frac{F(u)}{M} - g \cdot du + v(0) \]

where \( v(0) \) is the downward vertical velocity at the moment of contact.

The velocity is then expressed as:

\[ v(t) = \frac{F_{\text{max}}}{M} \frac{T_c}{\pi} \cos \left( \frac{\pi}{T_c} \cdot t \right) + \frac{F_{\text{max}}}{M} \frac{T_c}{\pi} - gt + v(0) \]

Knowing that at the middle of the contact the vertical velocity is null:

\[ \frac{T_c}{2} = 0 = \frac{F_{\text{max}}}{M} \frac{T_c}{\pi} - g \cdot \frac{T_c}{2} + v(0) \]

\[ v(0) = g \cdot \frac{T_c}{2} \cdot \frac{F_{\text{max}}}{M} \cdot \frac{T_c}{\pi} \]

Thus, the final expression of the velocity is obtained:

\[ v(t) = \frac{F_{\text{max}}}{M} \frac{T_c}{\pi} \cos \left( \frac{\pi}{T_c} \cdot t \right) - gt + g \cdot \frac{T_c}{2} \]  

[3]

**Calculation of the vertical displacement:**

By integrating the above expression of the velocity:

\[ z(t) = \int_0^t v(u) \cdot du + z(0) \]

where \( z(0) \) was the vertical position of the centre of mass at touch-down.

Assuming that \( z(0) = 0 \) and substituting [3] in the above equation:

\[ z(t) = \int_0^t \left[ \frac{F_{\text{max}}}{M} \frac{T_c}{\pi} \cos \left( \frac{\pi}{T_c} \cdot u \right) - g \cdot u + g \cdot \frac{T_c}{2} \right] \cdot du \]

The equation for the displacement is then:

\[ z(t) = \frac{F_{\text{max}}}{M} \frac{T_c}{\pi^2} \sin \left( \frac{\pi}{T_c} \cdot t \right) - \frac{1}{2} g \cdot t^2 + g \cdot \frac{T_c}{2} \cdot t \]  

[4]

In order to calculate the stiffness, the total displacement at the middle of the contact is calculated:

\[ z(\frac{T_c}{2}) = \frac{F_{\text{max}}}{M} \frac{T_c}{\pi^2} + g \cdot \frac{T_c^2}{8} \]  

[5]

**The stiffness calculation:**

The stiffness is the ratio of the peak force of the total displacement:

\[ K = \frac{\frac{F_{\text{max}}}{M} \frac{T_c}{\pi^2} - z(0) \cdot \frac{T_c}{2}}{z(\frac{T_c}{2}) - z(0) \cdot \frac{T_c}{2}} \]

Using the expressions [2] of \( F_{\text{max}} \) and [5] of \( z(\frac{T_c}{2}) \), the final equation is:

\[ K = \frac{\pi \cdot (T_v + T_c)}{T_c^2 \cdot \frac{T_v + T_c}{\pi} \cdot \frac{T_c}{4}} \]

As result, the stiffness can be calculated by measuring the contact time \( (T_c) \) and the flight time \( (T_v) \) directly determined by the Ergojump©.