CONTROL OF LEG STIFFNESS AND ITS EFFECT ON MECHANICAL ENERGETIC PROCESSES DURING JUMPING ON A SPRUNG SURFACE

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INTRODUCTION: In normal daily activity as in sports, humans adjust their physical behavior depending on the ground surface characteristics (Farley et al., 1998; Ferris, Liang & Farley, 1999) by being able to vary their performance (Arampatzis, 1999; Sanders, 1993). A difference in surface stiffness leads to a change in leg stiffness (Farley et al., 1998; Ferris, Liang & Farley, 1999). There are published results on relationships between joint stiffness and oxygen consumption (Dalleau et al., 1998; Heise & Martin, 1993). From this research, it can be concluded that leg stiffness influences athletic performance. The relationship between leg stiffness and performance during explosive movements on a sprung surface has not been reported in the literature to date. Leg Stiffness can be influenced by stride frequency while running (Farley & Gonzalez, 1996) or hopping frequency when bouncing in place (Farley & Morgenroth, 1999). These findings support the idea that it is possible to control leg stiffness by manipulating ground contact times and to consider its effects on mechanical energetic processes during drop jumps on a sprung surface. The purpose of this study is two-fold:

a. Examinations of the effect of verbal instructions, given to the subjects for the control of lower -extremity stiffness.
b. Assessment of the effect of the leg stiffness on mechanical energetic processes during drop jumps on a sprung surface.

METHODS: 10 female athletes participated in this study. The subjects performed drop jumps (DJ) on a sprung surface from two different heights (20 and 40 cm). The sprung surface was mounted on a "Kistler" force plate. The instructions given to the subjects were as follows: "jump as high as you can" and "jump high a lit7tle faster (regarding the ground contact time) than your previous jump". The jumps were performed at each height until the athlete could not achieve a shorter ground contact time. Four jumps per subject and height were selected for analysis. Ground reaction forces were measured using a force plate (1000 Hz). The jumps were recorded using a high-speed (250 Hz) digital camera. The deformation of the sprung surface was measured by recording the motion of a reflective marker, placed under the surface using a digital camera operating at 500 Hz. Surface electromyography (EMG) was used to measure muscle activity (1000 Hz) in 5 muscles, (gastrocnemius lateralis, gastrocnemius medialis, tibialis anterior, vastus lateralis and hamstring) of the left leg.
All analyzed jumps were divided into 4 groups. Group 1 contained the jump from each subject with the longest contact time. Group 4 contained the jumps with the shortest contact times. Groups 2 and 3 contained the 2 remaining jumps from each subject, which were assigned to the given groups based on contact time. The differences among groups were checked using a t-test for paired subjects. The level of significance was set at $p<0.05$. Pearson's correlation coefficients were calculated to examine the relationships between the different parameters.

RESULTS AND DISCUSSION: The high linear relationship between force, change in position of the center of mass and also between moment and change in angle, (tables 1 and 2) supports the hypothesis that, during drop jumps on a sprung surface, leg stiffness, ankle stiffness and knee stiffness can be approximated, using one linear spring and two rotational springs. It is possible to induce changes in leg stiffness during drop jumps on a sprung surface, by controlling ground contact times. Shorter contact times produce higher leg stiffness values. Similar influences on leg stiffness were found during running (Farley & Gonzalez, 1996) as well as in hopping (Farley et al., 1991; Farley & Morgenroth, 1999).

Table 1 **Support time ($t_{support}$), Leg Stiffness (K_{Leg}), Ankle Stiffness (K_{Ankle}) and Knee Stiffness (K_{Knee}) during Drop Jumps from 20 cm [Mean (SD), n=10]**
^{1,2,3}: Statistically Significant ($p<0.05$) Difference at Various Groups

Parameter (DJ 20cm)	Group1	Group2	Group3	Group4
$t_{support}$ [ms]	227 (24)	188 (9) ^{1}	175 (7) ^{1,2}	165 (7) ^{1,2,3}
K_{Leg} [kN/m]	27.66 (8.36)	47.86 (7.58) ^{1}	60.71 (10.21) ^{1,2}	80.94 (16.81) ^{1,2,3}
r^2_{Kleg}	0.95 (0.05)	0.97 (0.02)	0.96 (0.02)	0.96 (0.03)
K_{Ankle} [Nm/°]	9.80 (2.96)	15.73 (4.90) ^{1}	19.27 (4.04) ^{1,2}	22.94 (8.36) ^{1,2}
r^2_{KAnkle}	0.92 (0.07)	0.98 (0.02) ^{1}	0.98 (0.01) ^{1}	0.98 (0.02) ^{1}
K_{Knee} [Nm/°]	27.52 (18.54)	55.84 (20.86) ^{1}	68.59 (32.36) ^{1}	-
r^2_{KKnee}	0.88 (0.08)	0.81 (0.15)	0.87 (0.13)	-

Table 2 **Support Time ($t_{support}$), Leg Stiffness (K_{Leg}), Ankle Stiffness (K_{Ankle}) and Knee Stiffness (K_{Knee}) during Drop Jumps from 40 cm [Mean (SD), n=10]**
^{1,2,3}: Statistically Significant ($p<0.05$) Difference at Various Groups

Parameter (DJ 40cm)	Group1	Group2	Group3	Group4
$t_{support}$ [ms]	217 (15)	186 (9) ^{1}	173 (7) ^{1,2}	164 (6) ^{1,2,3}
K_{Leg} [kN/m]	30.90 (8.68)	48.00 (11.18) ^{1}	55.39 (7.82) ^{1,2}	62.46 (9.97) ^{1,2}
r^2_{KLeg}	0.92 (0.07)	0.96 (0.02)	0.96 (0.02)	0.96 (0.02)
K_{Ankle} [Nm/°]	12.30 (6.77)	13.98 (2.99)	16.13 (4.80)	17.74 (4.35) ^{1,2}
r^2_{KAnkle}	0.96 (0.03)	0.93 (0.10)	0.97 (0.03)	0.96 (0.04)
K_{Knee} [Nm/°]	22.08 (8.37)	46.23 (22.48) ^{1}	79.89 (32.28) ^{1,2}	121.08 (44.16) ^{1,2,3}
r^2_{KKnee}	0.85 (0.08)	0.90 (0.07)	0.86 (0.10)	0.88 (6.29)

The leg stiffness appears to be influenced by both, ankle and knee stiffness (tables 1 and 2). The correlations between leg and joint stiffness are higher at the knee (DJ20cm: $r_{Ankle}=0.52$, $p<0.01$, $r_{Knee}=0.69$, $p<0.01$; DJ40cm: $r_{Ankle}=0.18$, n.s, $r_{Knee}=0.74$, $p<0.01$). Leg stiffness has a positive influence on the amount of energy stored in the sprung surface and hence in the amount of energy flowing back during the positive phase (figure 1 and 2). The energy transmitted to the sprung surface is 25% to 45% of the total body energy decrease, experienced by the subject during the negative phase. The amount of energy flowing back from the sprung surface to the subject is between 20% and 35% of the total energy delivered to the human body during the positive phase. In spite of this, the total body energy and the vertical take off velocity of the center of mass are not significantly different in the first three groups. In fact, group 4 shows the lowest values for both parameters. The reason for this is that the energy delivered by the subject during the positive phase is considerably low for group 4. These results demonstrate that the maximization of the velocity of the center of mass and of the total body energy at take off, is not achieved by maximizing the energy transmitted to the sprung surface. In addition, there are diverse performance strategies leading to a maximization of the take off velocity and to the maximal total body energy at take off. Anderson and Pandy (1993) found a similar phenomenon within the muscle-tendon-complex by means of a simulation model of counter-movement jumps. Increasing the energy transmitted to the tendon led to a reduction of the energy produced by the contractile elements. The achieved jump height remained at almost the same level (Anderson and Pandy, 1993). Voigt et al. (1995) also were not able to find any correlation between the total positive work done, the jump height and the energy transmitted to the tendons during drop jumps. The results of this study differ from those reported by Sanders and Allen (1993). They measured higher jump heights during drop jumps on a sprung surface, when the amount of energy absorbed by the subject was reduced during the negative phase and through an increase of the energy transmitted to the sprung surface. This could not be confirmed in this study.

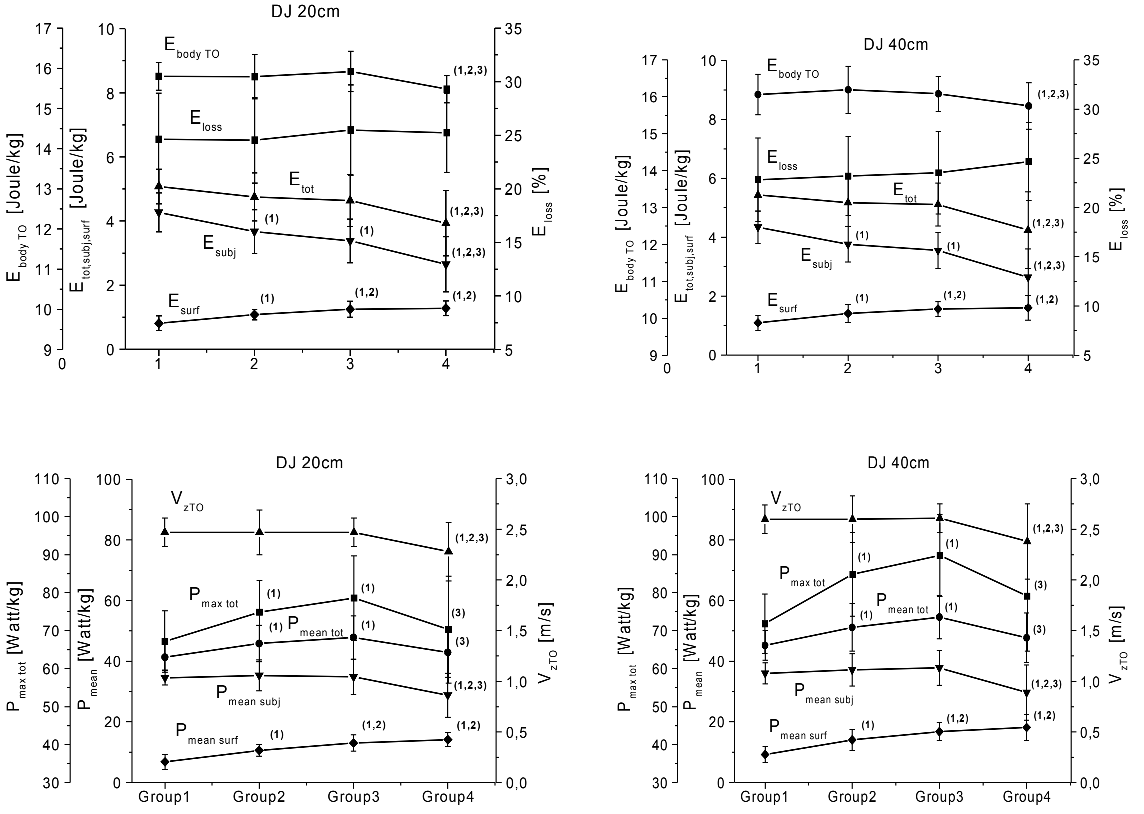

Figure 1 - Total energy of the human body at the take off ($E_{body\ TO}$), energy loss in sprung surface (E_{loss}), energy of the subject (E_{subj}), energy of the sprung surface (E_{surf}) and total energy (E_{tot}) during the positiv phase of the drop jumps (upper diagram row), vertical take off velocity (V_{zTO}), mean mechanical power of the subject ($P_{mean\ subj}$), mean mechanical power of the

sprung surface ($P_{mean\ surf}$), mean and maximum total mechanical power ($P_{mean\ tot}$, $P_{max\ tot}$) during the positive phase of the drop jumps (lower diagram row, n=10)^{1,2,3}: statistically significant ($p<0.05$) difference at various groups.

Mean and maximal total mechanical power, during the positive phase of the drop jumps are influenced by leg stiffness and show highest values in group 3. This indicates that there is an optimal leg stiffness value required to maximize the mechanical power during the positive phase of the drop jumps on a visco-elastic sprung surface. The increase in total mechanical power, apparent until group 3, results from the higher mechanical power of the sprung surface. On the other hand, the decrease seen in group 4 results from the lower mechanical power achieved by the subject. This means that the total mechanical work and the total mechanical power are dependent on both the behavior of the energy storing system (sprung surface) and that of the energy producing system (subject).

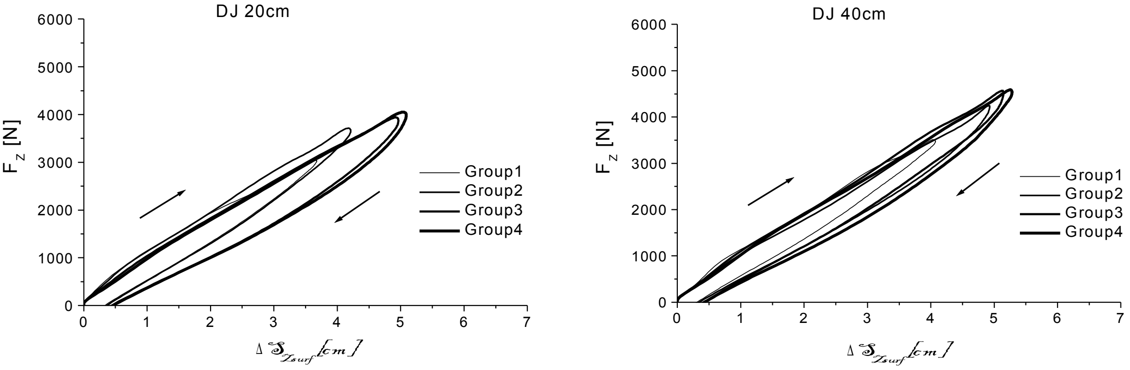

Figure 2 - Force-deformation curves of the sprung surface (n=10) (The loss of energy due to the visco-elasticity of the sprung surface is about 24 ±8.2 % of the energy transmitted to the surface).

Pre-activation times of the studied muscles did not change in relation to the changes in leg stiffness. The IEMG of the pre-activation phase showed differences and were related to the leg stiffness. This may indicate that it is not the amount of time of the pre-activation, but rather the activation level that causes the change in leg stiffness. Although it is possible to change leg stiffness by altering the body geometry at touch down (Farley et al., 1998), this was not the fact in this study because no differences in ankle, knee or hip angles could be found between the four groups. It would appear that the highest mechanical power values are not achieved by a maximal activation of the leg muscles. However, it is apparent that maximization of mechanical power is more likely to be achieved by an optimum activation of the leg muscles during the pre-activation phase.

From this study it can be concluded that the energy transmitted to the sprung surface, the energy produced by the subject during the positive phase and the total mechanical power during the positive phase during drop jumps, are all influenced by leg stiffness. An increase in leg stiffness causes an increase in the energy transmitted to and recovered from the sprung surface. This action simultaneously creates a decrease in the energy produced by the subjects. Therefore it is possible to achieve maximal vertical take off velocity of the center of mass and maximal take off body energy while experiencing different levels of leg stiffness. The maximization of mechanical power is achieved by optimal leg stiffness values and by the amount of activation of the leg muscles during the pre-activation phase. Furthermore the leg stiffness during drop jumps on a sprung surface can be controlled through the contact time. Shorter contact times produce higher leg stiffness values.

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