INFLUENCE OF FATIGUE ON LOWER EXTREMITY FUNCTION

G.-P. Brüggemann

Institute for Athletics and Gymnastics, German Sport University, Cologne, Germany

INTRODUCTION

Recent studies have indicated changes in lower leg kinematics occuring in different stages of endurance activites, presumably as a result of fatigue (e.g. Hamill et al., 1992; Williams et al., 1991; Siler and Martin 1991). Others have found differences in rearfoot motion in overground or treadmill running before and after exhaustion treatments. Hamill et al. (1988), Van Gheluwe et al. (1995) and Brüggemann et al. (1995) all found greater rearfoot angles during running after fatigue treatments although this result was not always statistically significant. Few relevant kinetic data are available e.g. ground reaction forces or resultant joint forces and moments. Brüggemann et al. (1994) reported a decreased impact during endurance running at constant speed sometimes accompanied by an increase in rearfoot motion during the early stance phase. Nicol et al. (1991a,b) studied the influence of exhausting running on neuromuscular performance. They found significant differences in parameters indicating power in lower leg activities during short stretch-shortening cycles before, during and after a marathon. Results published in Nicol et al. (1991a) indicated the impact and peak active ground reaction forces during the stance phase of a sprint test were lower after running a marathon. This pattern was found in both vertical and horizontal components. The duration of the stance phase increased. From these results they concluded that fatigue resulted in a reduced ability to sustain stretch loads. However, as the maximal velocity of the sprint decreased from one sprint test to the next, care must be taken in the interpretation of these results.

Nicol's results were supported by Gollhofer et al. (1987) dealing with EMG patterns during submaximal loads in stretch-shortening cycles of the triceps brachii muscle. These indicated modifications of neuromuscular performance after fatigue. It can be speculated that muscular and neural fatigue lead to significant changes in muscle activation patterns, which in turn influence the stiffness and probably the elastic energy storage capacity of the muscle-tendon complex. From this perspective most studies attempting to understand footwear function with the aim of impact cushioning at touchdown and control of rearfoot motion (e.g. Nigg and Ségesser, 1992) must be discussed with some reservation when applied to fatiguing actitivies. All studies investigating the absolute and relative motion of the rearfoot during diverse sport activities, the loading ground reaction forces or insole pressure distribution have been based upon the assumption of constant metabolic circumstances and stable neuromuscular control. Studies dealing with the leg-shoe-surface interface have not taken into account the muscular and neuromuscular control system of the human being in different metabolic and neural states.

Therefore, the purpose of the paper was to investigate the influence of different stages of muscular (or peripheral) and central fatigue on micro-control mechanisms and lower extremity function during running.

THE EXPERIMENTAL SERIES

A series of experiments was designed to determine the influence of muscular and central fatigue on lower extremity function. Study 1 covered the influence of aerobic and anaerobic induced fatigue on strength and muscular control of the lower extremities. Study 2 analysed the influence of local muscular fatigue of the shank muscles on lower extremity function during running and in study 3 fatigue was induced by running on a treadmill and lower extremity function was examined through the duration of the running treatment.

Thus, in the last two studies running speed and mechanical properties of the environment remained constant, whereas the different stages of fatigue were used as experimental variables.

STUDY 1

Methods:

The direct effect of aerobic and anaerobic loading on the control mechanism of lower extremity function was investigated by a dynamic leg-press test.A precise fatigue protocoll induced by treadmill running was administered prior to the leg-press. The sample was comrised of 12 male subjects (age: 22 ± 1.5 yrs).

The initial stage was a stepwise determination of the subjects' anaerobic thresholds. Then the isometric and dynamic strength were measured with a leg-press device instrumented with one three-dimensional, piezo-electric load cell (Kistler™). Dynamic leg extension was executed under loads of 400 N (of the sled) and then 15 %, 20 %, and 25 % of the isometrically produced force maximum. Subsequently the subjects were fatigued with an aerobic loading protocoll involving 30 minutes of treadmill running while maintaining less than 5 mmol/l lactate.After a rest period of several days anaerobic loading was induced by running on a treadmill for one minute while constantly exceeding 5 mmol/l lactate.

The subjects' dynamic strength was measured under the four described conditions immediately after fatigue had been induced. In the dynamic leg-press test the three orthogonal reaction forces at the foot-machine interface were measured. Maximum values and force rates were determined.All forces were normalised to body weight. The experimental setup had been designed to test the efficiency of a movement with a clearly defined aim: the task of pushing the leg press with maximum force, implying that the direction of the force administered should be normal to the sled. Any increase in horizontal forces would indicate impaired motor control.

Results:

Under the treatment of anaerobic loading the forces before and after the treatment showed no significant differences in the normal direction at any of the loads but there was a statistically significant increase in the sagittal and transverse forces (figure 1). In a comparison of the effects of the aerobic and anaerobic treatments anaerobic fatigue produced greater variations in the transverse and sagittal forces (figure 2).

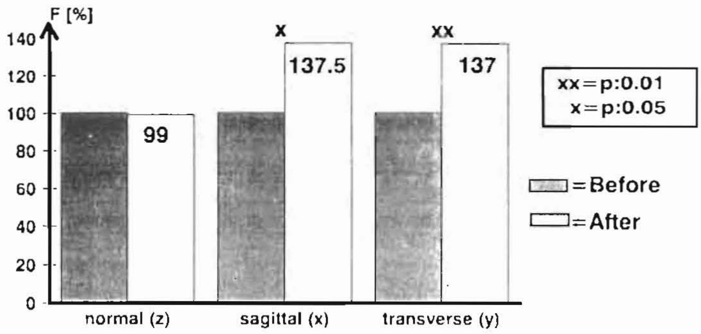

Figure 1. The effect of anaerobic fatigue at 20% of max. isometric load

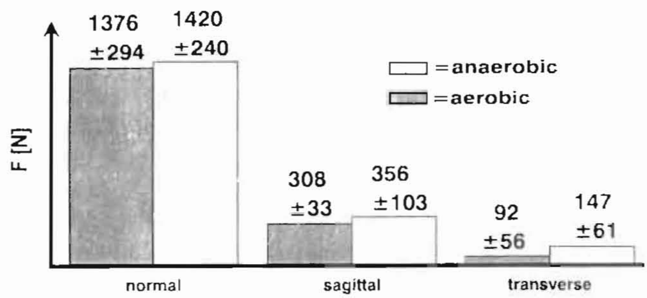

Figure 2. Comparison of aerobic and anaerobic fatigue effects at 20% of max. isometric load

The force rate decreased with fatigue for all four dynamic conditions of leg extension and the effect induced by anaerobic fatigue was also greater than for aerobic loading although this difference was not significant.

Conclusion:

Both aerobic and anaerobic load can lead to a disturbance of fine motor control and coordination. Anaerobic loading tends to have a greater influence than moderate aerobic loading.

STUDY 2

Methods:

In a second study the influence of defined local fatigue of the shank muscles on lower extremity function during running was examined on five male subjects (age 26 ± 3.0 yrs).

The shank muscle training device required the seated subject to voluntarily rotate a pedal from an inverted/adducted position in a downward arc to an everted/abducted position and back in an upward arc against the weight of an eccentric bar

The subjects were required to complete as many of these cycles as possible in two minutes. EMG recordings conducted during the fatigue treatment showed that m. tibialis anterior and m. peroneus longus were the primary muscles activated by the loading device.

After five minutes of adaptation to treadmill running at 3.5 m/s kinematic and kinetic variables and EMG signals were measured. The shank muscles were then locally loaded using the training device. Immediately after the treatment the subjects entered the treadmill again and data were collected a second time.

Vertical ground reaction forces were measured using piezo-electric force transducers located under the rotating belts of the treadmill (GaitKinetics™). An in-shoe goniometer registered the rearfoot angle (ß). The angle ß incorporated movements of both the talo-crural and the talo-calcaneal joints and therefore, defined the absolute position angle of the calcaneus relative to the shank. In addition three-dimensional lower leg kinematics were calculated (PEAK Performance™ motion analysis system) at 50 Hz from the images of three Hi8 video cameras.

EMG (ERNST system) signals from the m. triceps surae, the m. tibialis anterior, m. peroneus longus, m. vastus lateralis and m. biceps femoris were pre-amplified and registered simultaneously with the kinetic and kinematic data. Data were collected for a sequence of 20 footfalls and these were averaged before further analysis. From the angle-time history the value of ß at touchdown ($ß_{TD}$) and takeoff ($ß_{TO}$) and the maximum angle during the stance phase were registered. The ground reaction force data reduction included the impact peak (F1), the active force maximum (F2) and the relevant times.

Results:

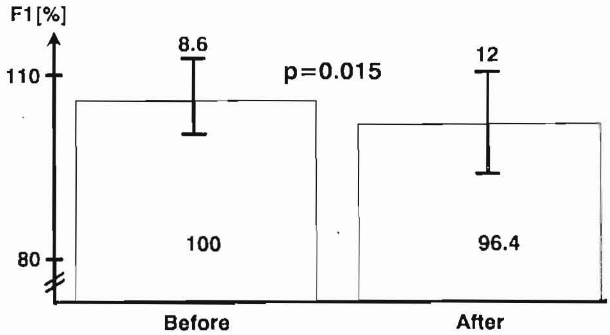

Figure 3. Impact before and after local muscular fatigue

The normalised force data showed a significant decrease in F1 between the pre-, and post-treatment values (figure 3). No significant difference was found in F2. The matching time intervals indicated a longer contact phase and a trend to a later occurrence of F1 and F2 induced by muscular fatigue.

$ß_{TD}$ increased slightly (mean: + 2.2°). The change in ß (Δ ß) from touchdown to maximum ($ß_{max}$) also increased following the muscular fatigue treatment (mean:

+ 3.2°). It is therefore, suggested that fatiguing m. tibialis anterior and m. peroneus longus can be related to a reduction of stiffness of the muscles supporting the ankle joint and consequently to a decreased impact peak. In addition ($ß_{TD}$) indicated impaired muscular control prior to touchdown after the treatment resulting in an increased range of motion (Δ ß). Surprisingly ($ß_{max}$) during stance showed no difference after fatigue.

The EMG recordings showed a time shift of muscle activation to the right for all analysed muscles. The local fatigue treatment seemed to not only influence the dorsiflexor but also the knee extensor muscles. Mean power frequency (MPF) of the m. vastus lateralis decreased, despite this muscle group not being specifically fatigued by the treatment. However, the MPF of the locally fatigued m. tibialis anterior increased significantly after the fatigue treatment. During fatiguing slow-twitch fibers are activated and subsequently fatigued first (Gollnick et al., 1972), from the data of our study it can be speculated that the fast-twitch fibers were then recruited and the MPF increased again. It appears that the treatment with the training device used in this study fatigued the slow-twitch fibers; the fast-twitch fibers of m. tibialis anterior were then recruited in the running following the treatment.

Conclusion:

Local fatigue was related to decreased impacts indicating modified stiffness regulation and it may lead to changes in rearfoot kinematics. Local fatigue loading modified muscle firing patterns and therefore, affected micro-control mechanisms. Furthermore, local fatigue of foot and shank muscles appeared to influence control patterns of the thigh musculature during running.

STUDY 3

Methods:

Ten male subjects (age:29 $\pm$ 5.6 yrs) ran 45 minutes on the instrumented treadmill with a speed chosen between 2.6 and 3.0 m/s depending upon individual endurance ability. All subjects were familiar with treadmill running but not particularly well trained (< 15 km/week). As some subjects were volitionally exhausted before 45 minutes, a complete data set was available for 35 minutes running for further analysis. Kinematic, kinetic and EMG data were collected as for the local fatigue experiment (study 2). The first data collection was executed after initial adaptation to treadmill running. Further data collection was conducted after every five minutes. Data were analysed using multiple variance analysis.

Results:

The stage of fatigue (running time) was treated as the varying factorThe horizontal bars in figures (4 and 5) indicate those data sets which showed significant differences ($p \leq 0.05$). The lines connect the mean values and the 95 % confidence intervals of the means are also indicated.The results presented in figures 4 and 5 are expressed in percentages of the mean of the second data collection executed 7 minutes after the start as this appeared to represent the stage at which the subjects had adapted to running on the treadmill.

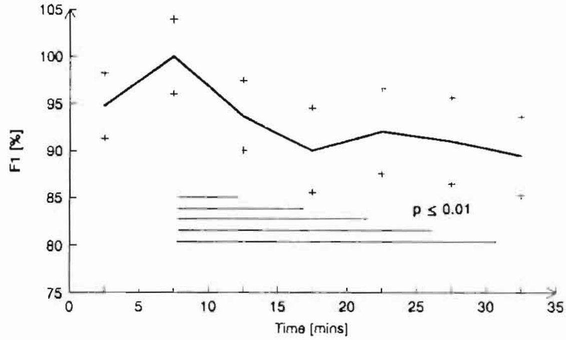

Figure 4. Impact during central fatigue treatment

Figure 4 indicates an increase in the peak force in the first five minutes of running. This was combined with a slight decrease in the time to peak.After this first phase of adaptation the peak forces constantly decreased throughout the loading time. All the means differed significantly from the second measurement. The decrease in the maximum impact peak was combined with an increase in time to peak but only the mean of the sixth measurement was significantly different from the second measurement.

The analysis of the active force during the pushoff and the matching time to the first maximum (F1) supported the notion of an early adaptive phase occuring from the very beginning to the second data collection at seven minutes. After this the active force decreased until the fourth data collection. Significant differences in mean forces existed between the second and all subsequent data sets.The early adaptive phase was the dominant feature of the time to peak force.

$ß_{TD}$ and the time to $ß_{max}$ showed changes after approximately 15 minutes of running. A rapid increase in $ß_{TD}$ indicated a significant disturbance in the pre ground contact control of the foot position. Figure 5 illustrates the gradually increasing pronatory motion occuring as fatigue increases which is in support of results presented in the literature. In combination with the increase in time to $ß_{max}$ we may interpret this as a fatigue induced effect of the ankle´s medio-lateral stabilising structures.

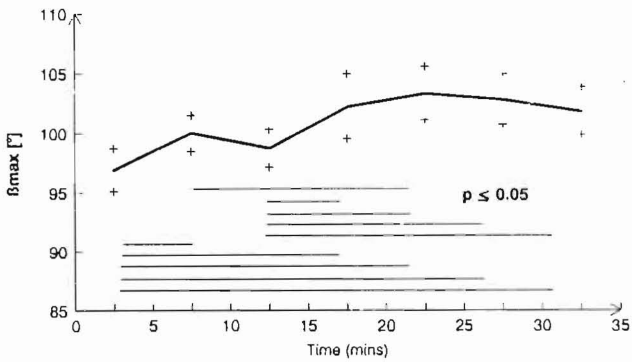

Figure 5. Rearfoot motion during central fatigue treatment

The MPF of m. tibialis anterior increased in the early phase of the treatment. As already indicated in study 2, treadmill running appeared to load this structure very strongly. Fast-twitch fibers were thus recruited relatively early resulting in the increased MPF of the m. tibialis anterior. A study presently being conducted on the activity of shank musculature during running at 4.5 m/s until volitional exhaustion will hopefully help to elucidate these mechanisms.

In the 150 ms interval prior to touchdown the MPF of the m. vastus lateralis decreased after approximately 7 minutes of running. Minimum values occured when data collection was performed for the third time, i.e. after approximately 12 minutes of running. It is interesting to note that this coincided with the previously discussed changes of the pattern of the rearfoot angle, ß.

The changes of the MPF of the m. vastus lateralis during the stance phase showed a very similar pattern as during preactivation. This indicated substantial fatigue of the knee extensor muscles after approximately 12 to 15 minutes of running.

Conclusion:

Kinematics and kinetics were significantly affected during the first ten minutes of running. A certain period was required for adaptation to treadmill running patterns. Fatigued running disturbed lower extremity kinematics in relatively untrained joggers. Rearfoot kinematics, impacts and muscle preactivity changed during fatigue as did activity patterns during the stance phase. Therefore, stiffness regulation seemed to be affected by fatigue. Mean power frequency diagnosis indicated two phase of fatigue: I. Fatigue of slow-twitch fibers and; II: Recruitment and fatigue of fast-twitch fibers.

SUMMARY AND CONCLUSION

Both kinematic and kinetic parameters measured on the lower extremity were significantly modified through fatigue produced by muscular work. The control of a defined motor task was negatively influenced by aerobic and anaerobic loading; undesired accessory forces perpendicular to the defined task increased after fatigue. The effect of fatigue was also studied in further experiments involving the more general movement patterns of running. It was expected that more uncontrolled movement resulting from fatigue would lead to greater passive (impact) forces in the short, eccentric stretch-shortening cycle of touch-down . However, the deceased forces presented in the results indicated that the collision occuring at impact may in fact be more a function of the stiffness of the muscle-tendon complex than purely neural control. Fatigue appears to result in changes in muscle activation patterns which are thus, assumed to be a contributing factor in modified muscle stifness prior to and during stance which is supported by data extracted from relevant literature. EMG parameters indicating such modified muscle stiffness were accompanied by a trend towards greater rearfoot motion after fatigue.

The results of this study combined with data presented in the literature showed that impaired stiffness regulation resulting from fatigue leads to changes in the collision experienced at impact. These changes may lead to inappropriate loading also affecting structures which remain unloaded in non-fatigue states. This was the case in the relatively controlled movements of normal running and pushing and would presumably be even more extreme in sports including sideways/cutting movements such as squash, basketball etc. Further research into sports injury mechanisms should therefore, include the factor fatigue.

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