

Running from Paris to Beijing: biomechanical and physiological consequences

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Abstract The purpose of this study was to examine the physiological and biomechanical changes occurring in a subject after running 8,500 km in 161 days (i.e. 52.8 km daily). Three weeks before, 3 weeks after (POST) and 5 months after (POST+5) running from Paris to Beijing, energy cost of running (Cr), knee flexor and extensor isokinetic strength and biomechanical parameters (using a treadmill dynamometer) at different velocities were assessed in an experienced ultra-runner. At POST, there was a tendency toward a ‘smoother’ running pattern, as shown by (a) a higher stride frequency and duty factor, and a reduced aerial time without a change in contact time, (b) a lower maximal vertical force and loading rate at impact and (c) a decrease in both potential and kinetic energy changes at each step. This was associated with a detrimental effect on Cr (+6.2%) and a loss of strength at all angular velocities for both knee flexors and extensors. At POST+5, the subject returned to his original running

patterns at low but not at high speeds and maximal strength remained reduced at low angular velocities (i.e. at high levels of force). It is suggested that the running pattern changes observed in the present study were a strategy adopted by the subject to reduce the deleterious effects of long distance running. However, the running pattern changes could partly be linked to the decrease in maximal strength.

Keywords Extreme exercise · Ultra-marathon · Human locomotion · Biomechanics

Introduction

Humans have adapted well to long distance running. This is likely due to evolutionary adjustments made during our hunting and scavenging days (Bramble and Lieberman 2004), including advanced skeletal design, our ability to sweat and our exceptional endurance capacity (Noakes 2006). Today, there are a number of ultra-endurance races around the world, performed on both roads and trails, many of them ranging between 100 km and 100 miles. The number of athletes competing in these events continues to rise, as evidenced by the increased number of new races being established each year (Knez et al. 2006). This growing interest in extreme endurance events has also stimulated research by the sports science community (Knechtle et al. 2008; Laursen et al. 2005; Skenderi et al. 2006; Weir 2000; Zouhal et al. 2009). For example, research has examined the effects of ‘classic’ ultra-marathon running on injuries and muscle damage (Holtzhausen et al. 1994; Kim et al. 2007), biochemical changes (Noakes and Carter 1982; Overgaard et al. 2002) and neuromuscular fatigue (Millet et al. 2002; Place et al. 2004).

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The longest competitive running event in the world is the ‘Self-Transcendence 3100 mile race’, an event run in New York that must be performed within a 51-day limit. However, ultra-marathon running is also performed during non-official events. For example, Dean Karnazes recently ran 50 marathons in 50 days over 50 US states. Serge Girard, who is also known for crossing the five continents without a single day rest, recently aimed to beat the non-official world record for the longest distance ran in 365 days; a record currently held by Tirtha Kuma Phani who ran 22,581 km in 365 days ($61.87 \text{ km day}^{-1}$). While these types of endurance feats are difficult to comprehend for some, they are nevertheless achieved by some incredibly gifted and motivated individuals. Still, nothing is known concerning the physiological and biomechanical consequences of such extreme endurance feats. The scientific question is important because it addresses the human adaptations that can potentially occur to afford this type of extremely hard exercise.

In 2008, we had the opportunity to monitor another ultra-runner, Philippe Fuchs, for potential changes in physiological and biomechanical parameters when he decided to run from Paris to Beijing (RPB, about 8,500 km in 161 days, i.e. 52.8 km, a distance about 25% longer than a marathon, per day for several months). Our aim was to analyze changes in muscle function and running patterns induced over the course of RPB. For that purpose, energy cost of running (Cr), isokinetic strength of the knee extensors/flexors as well as biomechanical running parameters were measured in this experienced ultra-marathon runner before, after and 5 months after his run.

Materials and methods

Subject

The subject of this case study was male, aged 58 years, having a stature of 1.73 m. Before and after the RPB, his body mass was 63.5 and 61.5 kg and body fat was 21.5% and 16.5%, respectively. He was an experienced ultra-endurance runner. The subject had completed a number of prior multi-stage runs. Indeed, for more than 20 years, he performed every summer a long (several days to several weeks) run. For instance, he ran from Nantes to Besançon (675 km in 10 days), from Paris to Barcelona in 1992 (880 km in 15 days), from Paris to North Cap (Norway) in 1995 (3,200 km in 8 weeks) or from Paris to Athens in 2004 (2,400 km in 6 weeks). The protocol, which was conducted according to the guidelines outlined in the 1964 Declaration of Helsinki, has been approved by the local ethics committee. The subject provided his written informed consent to partake in the study.

Procedures

The subject reported to the laboratory on three separate occasions: about 3 weeks before (PRE), 3 weeks after (POST) and 5 months after (POST+5) the RPB. He was familiar with running on motorized treadmills before his first visit. This is important because Cr decreased over the first sessions of treadmill running in unaccustomed runners (Brueckner et al. 1991). The first two sessions were organized in a similar fashion. For the measurement of biomechanical parameters during running, the subject was first asked to warm-up by running for 5 min at 8 km h^{-1} on a treadmill dynamometer (HEF Techmachine, Andrézieux-Bouthéon, France). The subject then ran for 2 min at 8 km h^{-1} , with 2 km h^{-1} increases in treadmill speed occurring every 2 min (with a 2-min pause between stages) until attainment of 16 km h^{-1} . After a 30-min break, body mass (BM), height and percent body fat were measured. The subject then performed an incremental test on a motorized treadmill (Gymrol S2500, HEF Tecmachine) that aimed at determining his Cr and submaximal blood lactate concentrations and heart rate. The first three stages were set at 8, 10 and 12 km h^{-1} and lasted for 4 min of running, followed by 1 min of rest for blood sampling. The subsequent stages were discontinuous, with speed progressively increasing by 1.5 km h^{-1} every 3 min, also followed by 1 min of rest for blood sampling. Such long stages were chosen to ensure steady state for $\dot{V}O_2$ measurements because energy cost was an important variable of this study. Discontinuous protocol was chosen for blood samples and for ECG recordings. Because the subject did not want to risk injury prior to the RPB, he opted to not run to exhaustion, and the last stage of testing was 16.5 km h^{-1} . As a result, $\dot{V}O_{2\text{max}}$ and maximal lactate concentration were not determined. About 45 min after the non-maximal incremental test, the subject performed the isokinetic strength measurements. During his third visit, the subject performed only the running bouts on the treadmill dynamometer and the isokinetic strength measurements. From POST to POST+5, after a few weeks of recovery, the subject returned to his normal training load.

Criterion measurements and data analysis

Gas exchange measurements

During the incremental test, measures of oxygen uptake and carbon dioxide production were determined during the last 45 s of each 3- or 4-min period. For this measure, the subject breathed through a two-way non-rebreathing valve (series 2700, Hans Rudolph, Kansas City, MO) connected to a three-way stopcock that stemmed into a 100 l Douglas bag. The volume of the expired gas was measured in a

Tissot spirometer (Gymrol, Roche-la-Molière, France) and fractions of gases were determined with a Zirconcell O₂ analyzer and an infrared CO₂ analyzer (Servomex 2240, Crowborough, England). The analyzers were calibrated with mixed gases; the composition of which was determined using Scholander's method. Cr was determined as the average value of $\dot{V}O_2$ at 8, 10 and 12 km h⁻¹.

Heart rate and lactate concentration

Heart rate throughout each test was determined via electrocardiogram (Cardiostest EK 51, Hellige, Freiburg, Germany), while blood was sampled from the fingertip after each stage of the test for lactate concentration ([La⁻]) using an enzymatic method (YSI 1500 Sport, Yellow Springs Instruments, Yellow Springs, OH). The blood lactate analyzer was calibrated before each test using standard solutions of 5 and 15 mmol l⁻¹.

Isokinetic strength

Knee flexion and extension muscle strength were measured isokinetically on the subject's left limb as maximum concentric knee torques using an isokinetic dynamometer (Con-Trex, CMV AG, Dübendorf, Switzerland). The dynamometer was calibrated according to the manufacturer's recommendations and following the instructions for optimal reproducibility. The subject remained in a seated position, with hip flexion angle held at 90°. Stabilization straps were positioned across the subject's chest, pelvis, and ipsilateral thigh. The lever arm shin-pad was placed just proximal to the malleoli. The subject performed two series of five graded submaximal repetitions at 120° s⁻¹ as an initial isokinetic familiarization and warm-up. Data were obtained at the four testing velocities of 60, 120, 180 and 240° s⁻¹ concentrically, with 4, 5, 5 and 6 repetitions, respectively. Before each testing velocity, the subject was familiarized using 4–6 submaximal repetitions at the considered velocity. One minute separated each set of movements. The subject was encouraged to work as hard as possible. The highest torque (in N m, expressed with gravity correction) generated during these trials was considered as the maximal peak torque at each velocity.

Running biomechanics

All biomechanical parameters described below were measured at 8, 10, 12, 14 and 16 km h⁻¹ using a treadmill dynamometer each stage lasting about 1 min. Using the same calibration procedure as Belli et al. (2001) did for validating a similar walking treadmill, the treadmill static non-linearity was determined to be less than 0.5 and

1%, respectively, in vertical and horizontal directions. The measured natural vibration frequency (treadmill hit with a hammer) was 147 Hz in the vertical direction and 135 Hz in the anterior–posterior and medio-lateral directions. Vertical ground reaction force (F) data and treadmill belt velocity (v) were sampled at a rate of 1,000 Hz. The reference period considered for running kinematics in the present study was the step, i.e. the time period from the onset of one foot contact to the onset of the contralateral foot contact. All biomechanical parameters were measured for each step and were averaged over ten consecutive steps.

Running kinematics

Contact (t_c) and aerial (t_a) times were measured from $F(t)$ signals, expressed in s, and further used to compute the subject's step frequency (F_q , Hz):

$$F_q = (t_c + t_a)^{-1}$$

The duty factor (DF) was calculated as follows:

$$DF = t_c(t_c + t_a)^{-1}$$

Running dynamics and mechanical work

The peak vertical ground reaction force measured during the contact phase (F_{max}) was characterized. The mean loading rate was also determined as the mean slope of the vertical ground reaction force from touch down to the passive peak. The external mechanical work (W_{ext} , J kg⁻¹ m⁻¹) developed at each step to move the center of mass in the sagittal plane was computed from potential and kinetic energy changes in the center of mass (for details, see Cavagna et al. 1964; Cavagna 1975). This was calculated as the sum of potential (W_{pot}) and kinetic (W_{kin}) works, which were obtained from vertical and antero-posterior force signals allowing the computation of vertical displacement and horizontal velocity of the center of mass over time, by, respectively, double integration of vertical acceleration and single integration of horizontal acceleration (obtained from force measurements), according to the method proposed by Cavagna (1975) as follows.

Potential and kinetic works were calculated from changes in potential and forward kinetic energies of the center of mass over a complete step:

$$W_{pot} = mg\Delta h$$

with m the subjects' body mass (kg), g the acceleration of gravity (m s⁻²), and Δh the difference between the highest and the lowest vertical positions of the CM over one complete step (m) and:

$$W_{kin} = 0.5m(v_{max}^2 - v_{min}^2)$$

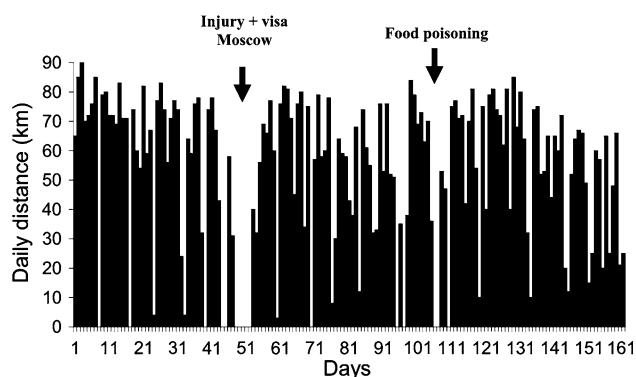


Fig. 1 Self-reported daily running distance. Two main stops can be distinguished over the 161 days: one in Moscow for injury plus administrative problems (visa) and one in Kansk for food poisoning

v_{\max} and v_{\min} being, respectively, the maximal and minimal horizontal velocities of the CM during the complete step (m s^{-1}).

Since this methodology was initially developed to compute external work during level running on a force plate and not during running on a treadmill, care was taken to ensure that the subject ran in the same relative horizontal position with respect to the treadmill belt, to ensure that no overall forward or backward displacement of the center of mass occurred, since the method used to compute external work assumes constant average velocity of forward displacement (Cavagna 1975). This is a limitation of the use of treadmill dynamometers to compute external work since, by definition, the center of mass of the body is assumed not to move horizontally with respect to the treadmill belt, yet this belt moves with respect to the center of mass. Also, the requirement for constant treadmill belt speed was not strictly met by the instrumented treadmill used in the present study, the absolute percent variations being within a $\pm 5\%$ maximum range (personal data).

Results

Daily running distance for the RPB is shown in Fig. 1. The blood lactate concentration–speed and heart rate–speed

relationships are presented in Table 1. Gross Cr was 160.4 and 170.3 $\text{ml O}_2 \text{kg}^{-1} \text{km}^{-1}$ before and after the RPB, respectively (difference PRE – POST +6.2%).

The main kinematic and dynamic variables are presented in Figs. 2 and 3. While contact time did not change, there was a general tendency toward a ‘smoother’ running pattern between PRE and POST (i.e. a higher F_q and DF along with a lower t_a). This was accompanied by lower vertical forces; both F_{\max} and loading rate at impact (Fig. 3). This ‘smoother’ pattern can also be observed throughout the evolution of W_{pot} , W_{kin} and W_{ext} at POST compared with PRE (see Table 2). At POST+5, the subject tended to return to the PRE running pattern at low ($8\text{--}12 \text{ km h}^{-1}$) but not at high speeds (14 and 16 km h^{-1}).

Knee flexion and extension isokinetic muscle strength at PRE, POST and POST+5 are presented in Fig. 4. At POST, there was a strength loss at every angular velocity for both knee flexors and extensors. When considering the knee extensor muscle contraction, the higher the angular velocity, the larger the strength loss between PRE and POST (-22% at 60° s^{-1} vs. -28% at 240° s^{-1}) but this was not the case for the flexor muscles. At POST+5, a clear improvement was noticeable for both knee extensors and flexors, with the exception of incomplete recovery at low angular velocities for knee extensors.

Discussion

While adventure runners like Serge Girard have performed longer distances without a single day rest, running from Paris to Beijing represents an extremely challenging experience. As such, the present case study represented a unique opportunity to examine human biomechanical and physiological adjustments to such an extreme exercise load. The main results of the present study were that a subject who was already an experienced ultra-runner before the RPB changed his running pattern to a ‘smoother’ locomotion after 5 months of running. Other important findings from the study were that (a) these adaptations were accompanied by a slight deterioration in Cr and a reduction

Table 1 Submaximal blood lactate concentration ($[\text{La}^-]$) and heart rate (HR) measured at different running speeds 3 weeks before (PRE) and 3 weeks after (POST) the run from Paris to Beijing

	8 km h^{-1}	10 km h^{-1}	12 km h^{-1}	13.5 km h^{-1}	15 km h^{-1}	16.5 km h^{-1}
$[\text{La}^-]$						
PRE	1.5	1.0	1.1	1.5	1.9	4.3
POST	1.2	1.1	1.5	1.6	2.2	4.4
HR						
PRE	92	114	118	136	148	162
POST	107	116	126	132	145	158

Metabolic measurements were not performed 5 months after the run from Paris to Beijing

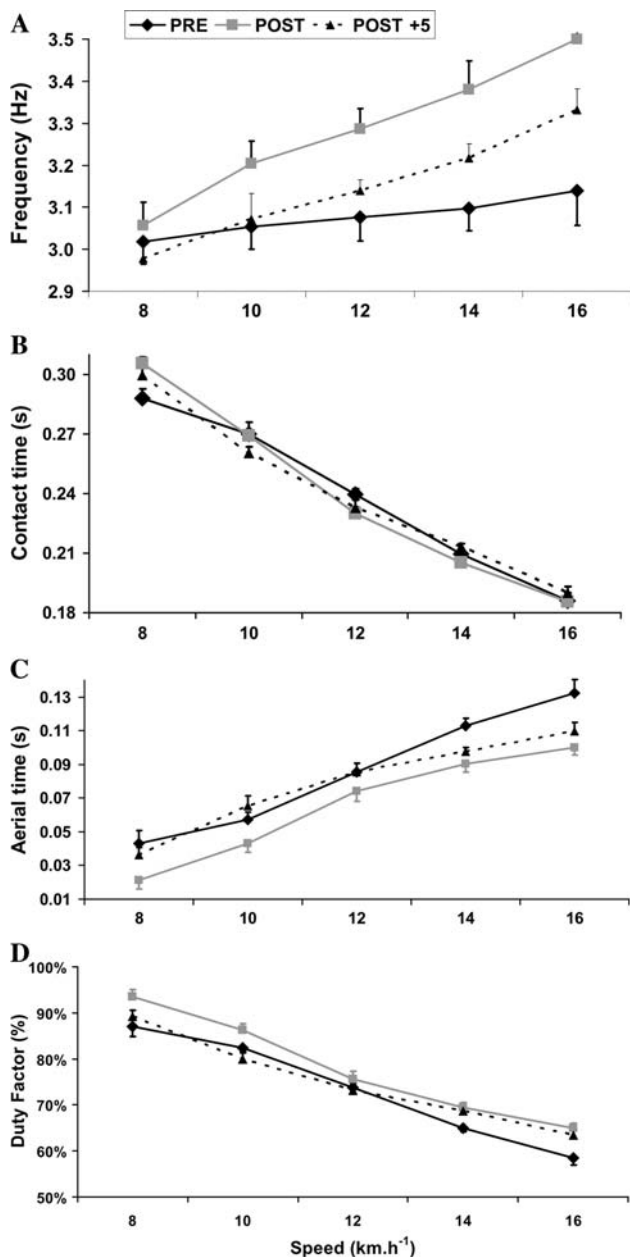


Fig. 2 Evolution (mean ± SD) of step frequency (a), contact and aerial times (b, c) and duty factor (d) at various running speeds measured 3 weeks before (PRE), 3 weeks after (POST), and 5 months after (POST+5) the run from Paris to Beijing

in maximal force generating capacities and (b) 5 months after completing the RPB, the subject had still not fully recovered maximal strength at high force levels and his running patterns at high speed. Some changes may have occurred in the 3 weeks between the end of the RPB and the POST measurements so the present data should probably be seen as the minimum changes induced by this extreme run.

No major changes were observed for heart rate or blood lactate concentration at a given submaximal running speed.

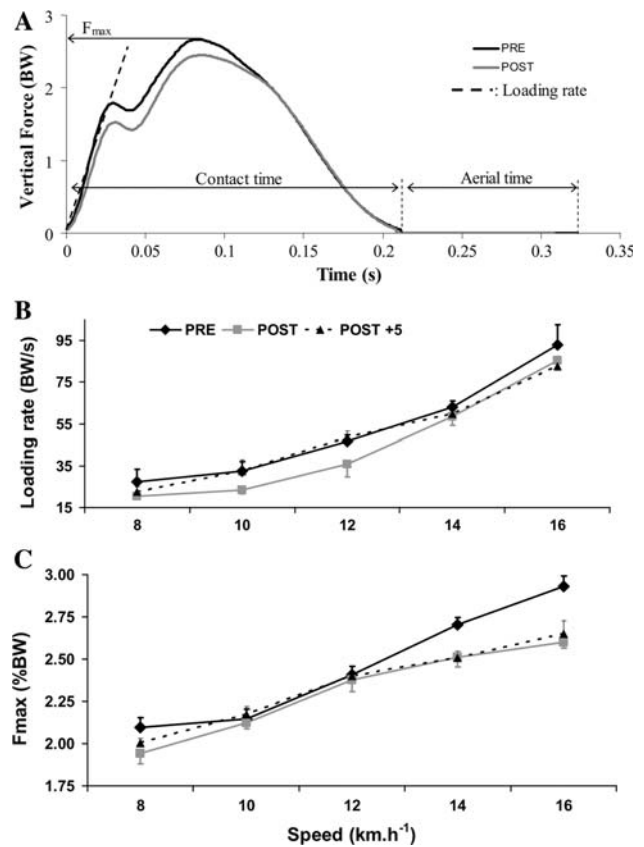
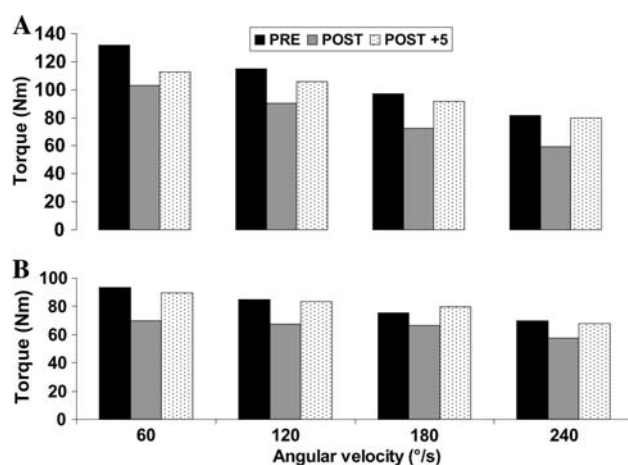


Fig. 3 Typical representation of the vertical force-time curve 3 weeks before (PRE) and 3 weeks after (POST; a) the run from Paris to Beijing and evolution (mean ± SD) of the mean load during impact (loading rate) at various running speeds (b) measured at PRE, POST and 5 months after (POST+5) the run from Paris to Beijing. The evolution (mean ± SD) of the peak vertical force (F_{max}) is also shown (c)

On the contrary, marked and consistent modifications in running pattern were shown in the kinematic, dynamics of the running step and mechanical work data from PRE to POST at all speeds. These results likely occurred to minimize the vertical and antero-posterior velocity and displacement of the center of mass as well as the impact load and maximal force occurring during the propulsive phase. While contact time was not modified, the subject did re-organize his running pattern toward that of a lower aerial time and a higher duty factor, therefore leading to a higher step frequency. Interestingly, we have recently reported (Morin et al. 2009) that a biopsy performed in the *vastus lateralis* muscle has biomechanical consequences comparable to the adaptations observed in the present study (i.e. higher frequency and duty factor and a lower aerial time). As with the present study in the POST condition, force application parameters were significantly lowered post-biopsy (Morin et al. 2009). These results were interpreted as subjects tending toward a “safer” style of running, with subjects limiting the amplitude of muscular recruitment at

Table 2 Mean (\pm SD, $\text{J kg}^{-1} \text{m}^{-1}$) values for the potential (W_{pot}), kinetic (W_{kin}) and external (W_{ext}) mechanical work measured at different running speeds 3 weeks before (PRE), 3 weeks after (POST), and 5 months after (POST+5) the run from Paris to Beijing

	8 km h^{-1}	10 km h^{-1}	12 km h^{-1}	14 km h^{-1}	16 km h^{-1}
W_{pot}					
PRE	0.75 \pm 0.02	0.62 \pm 0.02	0.59 \pm 0.03	0.56 \pm 0.02	0.52 \pm 0.03
POST	0.66 \pm 0.02	0.58 \pm 0.02	0.55 \pm 0.02	0.48 \pm 0.02	0.42 \pm 0.02
POST+5	0.72 \pm 0.02	0.63 \pm 0.03	0.58 \pm 0.02	0.50 \pm 0.01	0.45 \pm 0.01
W_{kin}					
PRE	0.35 \pm 0.04	0.48 \pm 0.07	0.55 \pm 0.03	0.55 \pm 0.03	0.62 \pm 0.04
POST	0.29 \pm 0.04	0.41 \pm 0.04	0.48 \pm 0.03	0.55 \pm 0.03	0.60 \pm 0.03
POST+5	0.38 \pm 0.03	0.44 \pm 0.04	0.49 \pm 0.04	0.56 \pm 0.05	0.64 \pm 0.04
W_{ext}					
PRE	1.10 \pm 0.06	1.10 \pm 0.08	1.14 \pm 0.06	1.11 \pm 0.03	1.13 \pm 0.05
POST	0.95 \pm 0.05	0.99 \pm 0.04	1.03 \pm 0.03	1.03 \pm 0.04	1.02 \pm 0.03
POST+5	1.10 \pm 0.03	1.07 \pm 0.06	1.07 \pm 0.04	1.07 \pm 0.06	1.09 \pm 0.04

**Fig. 4** Isokinetic concentric knee extension (a) and flexion (b) torques at different angular velocities measured 3 weeks before (PRE), 3 weeks after (POST), and 5 months after (POST+5) the run from Paris to Beijing

landing (through a lower loading rate) and during the step (lower F_{max}). Together, this resulted in a “smoother” stride, and a lower change in antero-posterior vertical velocity and displacement of the center of mass over a step (lower W_{pot} , W_{kin} and W_{ext}). One limit of the present study is nevertheless the fact that POST-RPB measurements were not made until 3 weeks after the run, permitting changes that may have occurred to mitigate so it cannot be ruled out that the adaptations were even larger.

In the present study, the biomechanical parameters returned to their PRE-RPB values at POST+5 at low speeds only (8–12 km h^{-1}). At higher speeds (14 and 16 km h^{-1}), the running patterns were similar to those found at POST. It is speculated that the subject was able to ‘tolerate’ a normal running pattern at low speeds, but

changed to a safer mode when the running speed and associated mechanical stresses were increased.

It must be mentioned that the biomechanical changes were associated with a slightly depreciated Cr, since this parameter was deteriorated by 6.2%, as it occurred with acute fatigue (Brueckner et al. 1991). It has been reported that Cr was negatively related to body mass (Lacour 1996). As a result, the Cr measured before RPB in a 63.5 kg subject can be considered as low. This can probably be explained by the training history of this subject since training in endurance running may decrease Cr (Lacour 1996) even if no data exist to our knowledge on very experienced ultra-endurance runners.

While Cr increased by about 6%, the external mechanical work decreased by 12% (when considering only 8–12 km h^{-1}) so that the mechanical efficiency of external work performance decreased by about 16%. One could suggest that this indicates a substantial deterioration of muscle bioenergetics brought about by the RPB. Nevertheless, the main explanation to the deteriorated Cr with a lower W_{ext} probably deals, at least partly, with internal work linked to the higher step frequency (Minetti 1998).

It has been shown that running velocity is set by $\dot{V}O_{2\text{max}}$, its maximal sustainable fraction, and Cr (Di Prampero et al. 1986). Indeed, possessing a good running economy has been suggested as being essential for ultra-marathon running performance (Jung 2003), particularly in subjects with comparable $\dot{V}O_{2\text{max}}$ and $\% \dot{V}O_{2\text{max}}$ sustained during competition (Scrimgeour et al. 1986). However, the task of running from Paris to Beijing is much different compared with traditional ultra-marathon performances. In fact, the main running factor to consider during extreme low intensity running is probably not Cr, but the ability to preserve muscle, tendon and cartilage structure, that could

be damaged by long distance running (Kim et al. 2007). It might then be considered that the running pattern adaptations observed in the present study were aimed at minimizing muscle lesion in order to allow completion of the 8,500 km trip.

Strength losses from PRE to POST were consistently detected in both extensor and flexor muscles at all angular velocities, a finding that could be linked to muscular and/or neural changes. No biopsies or neuromuscular function investigation were conducted in the present study, so we can only speculate regarding the potential contributors to this loss. In particular, a decrease in fiber cross-sectional area (CSA) may be expected (Widrick et al. 1996). A change in muscle fibers type toward an increase of slow twitch fibers percentage and a decrease in IIX fibers might also be expected, but this would not markedly affect maximal torque since the CSA normalized peak fiber torque (P_0) has been found to be comparable among fiber types (Malisoux et al. 2007), at least at slow or moderate contraction velocities. Whether P_0 /CSA could be affected by such extreme exercise is unknown.

A reduction in maximal voluntary activation could also, in theory, explain the strength loss shown after the RPB. However, we have previously demonstrated that, while sedentary subjects have a lower maximal voluntary activation compared with trained athletes, there is no difference between endurance- and explosive-type athletes for this parameter when measured under isometric conditions (Lattier et al. 2003). It might be that the neural input is partly responsible for the higher loss of knee extensor angular velocity strength. In fact, even if 240° s^{-1} is not an explosive contraction, it is possible that the discharge frequency or the number of doublet or triplet impulses, which are known to affect explosive strength (Van Cutsem et al. 1998), were altered by RPB. However, why this result was not observed for the knee flexors is not clear. Little is known regarding the relative contributions of the descending drive, afferent feedback, spinal circuitry, and motor neuron properties to training (Duchateau et al. 2006) and even less is known concerning extreme training loads, such as running from Paris to Beijing. Further studies dedicated to the neuromuscular adaptations that occur following chronic extreme muscular loading are needed.

In conclusion, clear adaptations of running patterns together with knee extensor/flexor strength loss and a slight deterioration in energy cost of running were observed in a subject who ran from Paris to Beijing in 161 days. It is speculated that the changes in running patterns observed in the present study were a strategy adopted by the subject to reduce the deleterious effects of long distance running. However, it is not possible to rule out the fact that running pattern alterations are at least partly due to the decrease in maximal strength.

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