Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions

D. Kay [a], A. St Clair Gibson [b,*], M.J. Mitchell [c], M.I. Lambert [b], T.D. Noakes [b]

[a] *Human Movement Studies Unit, Charles Sturt University, Bathurst, NSW, Australia*
[b] *MRC/UCT Bioenergetics of Exercise Research Unit, Department of Health Sciences, University of Cape Town Medical School, Cape Town, South Africa*
[c] *Medical School, University of Aberdeen, Aberdeen, Scotland, UK*

Abstract

Aim. The purpose of this study was to determine the neuromuscular fatigue profiles during 100 s isometric (ISO), concentric (CON), and eccentric (ECC) activity.

Methods. Twelve subjects (age 25.1±3.7 years, mass 70.1±8.2 kg, mean±SD) performed ISO, CON and ECC maximal voluntary contractions and 100 s endurance trials on an isokinetic dynamometer. Raw EMG data were recorded throughout each trial from the rectus femoris of the right limb. Corresponding data for integrated electromyography (IEMG), percentile frequency shifts (MPFS) and peak torque output were divided into five 5 s epochs and subsequently normalised with the first epoch being the reference point, in order to assess changes over time.

Results. There were no significant differences between ECC, CON and ISO peak torque output (211±63 vs 169±41 vs 177±61 Nm; ECC, CON, ISO) and IEMG activity (280±143 vs 305±146 vs 287±143 mV; ECC, CON, ISO) during maximal contractions. Serial reductions in torque output were greatest in ISO in which torque output during the final epoch was 31±13% of initial values, similar to the final torque values in CON (58±15%), but significantly less than ECC (108.6±38.6%; $P<0.001$) values. In CON and ECC, IEMG was maintained (95±27% and 93±21%; CON and ECC), whereas IEMG for ISO decreased to 38±13% of initial values. The greatest reduction in MPFS occurred in CON (69±10%) compared to ISO (78±9%; $P<0.05$) and ECC (93±6%; $P<0.001$).

Conclusion. These data demonstrate distinct neuromuscular fatigue profiles for the different types of muscle contraction. Whereas eccentric activity was largely fatigue resistant, isometric and concentric contractions displayed different neuromuscular fatigue profiles. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Fatigue; Peripheral; Central; Electromyography

1. Introduction

The understanding of fatigue in human skeletal muscle during voluntary contractions remains incomplete. Fatigue has been defined as a decrease in force production [1–3] or an inability to regenerate the original force [4] in the presence of an increased perception of effort [5].

Fatigue has also been classified as being either central or peripheral in origin. Central fatigue is described as a reduction in neural drive or motor command to the muscle resulting in a decline in force or tension development

[5]. Peripheral fatigue is defined as a decrease in the force generating capacity of the skeletal muscle due to action potential failure, excitation contraction coupling failure, or impairment of cross-bridge cycling in the presence of unchanged or increased neural drive [6,7].

Surface electromyography (EMG) is a technique used to examine neural drive during fatigue. Integrated EMG (IEMG) analysis allows for determination of motor unit activation, while EMG signal frequency spectrum analysis is generally a reliable indicator of signal conduction velocity [8], although factors other than conduction velocity may affect the frequency spectrum during fatiguing contractions [9].

Most studies of neuromuscular activity and fatigue have evaluated isometric contractions. But isometric contractions may not be representative of muscle activity and fatigue development during human locomotion [10].

* Corresponding author. Tel.: +27+21-6867330; fax: +27+21-6867530.
E-mail address: agibson@sports.uct.ac.za (A. St Clair Gibson).

Indeed, available data suggest that the development of fatigue may be specific to contraction type, activity and duration [5,11]. Despite this, to our knowledge no study has previously compared neuromuscular fatigue profiles during isometric (ISO), concentric (CON) and eccentric (ECC) muscle activity, to establish if the profiles during these types of muscle activity are different.

Therefore, the purpose of this study was to compare the neuromuscular changes induced by maximal ISO, CON and ECC activity during a continuous exercise period of 100 s duration.

2. Methods

2.1. Subjects

Twelve subjects (11 males, 1 female) volunteered to participate in the study. All subjects participated regularly in sport at the recreational level. The study was approved by the Ethics and Research Committee of the relevant institutions and all subjects signed a letter of informed consent prior to their participation. Subject characteristics are presented in Table 1.

2.2. Anthropometry

Each subject's height and mass was recorded, and their body fat content was assessed using the sum of the skinfold measurements of the right triceps, biceps, subscapular and supra-iliac skinfold sites [12]. In addition, the anterior mid-thigh skinfold measurement, the sub-gluteal, mid-thigh and above-knee circumferences were recorded in the right limb to calculate the lean thigh volume (LTV) of the right limb. This technique for estimating LTV assumes the upper section of

the lower limb has the shape of a truncated cone. The technique was adapted from the technique described by Katch and Katch [13] and has been validated against LTV assessed by magnetic resonance imaging [14].

2.3. Assessment of muscle activity

Skeletal muscle torque output was measured using Kin-Com dynamometer (Chattanooga Group Inc., USA). Subjects were secured to the dynamometer via shoulder and waist strapping. To avoid interference with the placement of EMG electrodes the active leg was not stabilised. The axis of rotation of the dynamometer was visually aligned with the lateral femoral epicondyle with the lower leg attached to the lever arm at the level of the lateral malleolus. All subjects performed maximal and fatigue trials for ISO, CON and ECC contractions of the knee extensor muscles of the right leg. Maximal voluntary contractions (MVC) and corresponding endurance protocols of ISO, CON and ECC were performed in a randomised order. Experimental trials were performed on the same day with a rest period of 10 min between trials. The EMG electrodes remained attached to the rectus femoris muscle throughout the experiment.

2.4. Maximal testing

Maximal tests were performed following a standard warm-up protocol. EMG and torque data were subsequently collected for four separated trials of each of ISO, CON and ECC activity. The subjects were verbally encouraged during each test to exert maximum effort. The test with the highest values for ISO, CON and ECC protocols were used for subsequent analysis. For ISO the knee was positioned at an angle of 60°, with the reference point being full knee extension. Concentric and ECC contractions were performed isokinetically at 60° s^{-1} between 6° and 84°, again with full extension acting as the reference point.

2.5. Endurance protocol

Participants were instructed to begin maximal effort immediately, and not to 'save' effort for the final seconds of the test. Subjects were verbally encouraged throughout all trials to exert maximal effort. For the ISO activity, subjects were positioned as for maximal testing with knee angle at 60°. Subjects were instructed to maintain maximal force output for 100 s. The protocol for the CON and ECC activity lasted 100 s. The knee extensor muscles contracted through a range of 6°–84° at 60° s^{-1}. To minimise fatigue of the antagonist muscle group during the trial, contraction velocity for flexion was set at 120° s^{-1}. Subjects were instructed to use minimal force during this phase. Throughout all sessions, torque output

Table 1
Anthropometric data of subjects

Subject	Age (years)	Height (cm)	Mass (kg)	Body fat (%)	LTV (cc)
1[a]	26	167.0	56.0	23.7	2994
2	33	177.0	73.0	17.6	3896
3	31	174.0	58.0	13.1	3732
4	22	177.0	73.5	11.1	4317
5	23	179.0	79.0	14.2	5257
6	24	180.0	73.0	14.0	3430
7	26	169.5	71.5	10.4	4760
8	21	180.0	77.0	14.8	4871
9	26	170.0	58.5	6.4	4220
10	23	171.3	69.0	11.4	4632
11	22	171.0	72.2	19.0	4202
12	24	190.0	80.0	16.8	4227
Mean	25.1	175.5	70.1	14.4	4211.5
SD	3.7	6.4	8.2	4.5	635.3

[a] Female.

(Nm) was recorded using the Kin-Com data analysis software.

2.6. Electromyographic (EMG) data collection and analysis

Prior to testing on the dynamometer, active EMG electrodes with bandwidth of 20–500 Hz and sensitivity of <0.08 µV/V were attached to the belly of the rectus femoris muscle. The skin overlying the rectus femoris muscle was carefully prepared. Hair was shaved off, the outer layer of epidermal cells abraded, and oil and dirt removed from the skin with an alcohol swab. Triode electrodes (Thought Technology Triode™ MIEP01-00) were placed on the muscle belly, and linked via a fibre-optic cable to a Flexcomp/DSP EMG signal acquisition apparatus (Thought Technology, Montreal, Canada) and host computer. A 50 Hz line filter was applied during data collection to prevent interference from electrical sources. EMG data were sampled at 1984 Hz for the duration of all tests, thus yielding raw signals. Raw EMG signals were full wave rectified, movement artefact removed using a high-pass second order Butterworth filter with a cut off frequency of 15 Hz, then smoothed with a low-pass second order Butterworth filter with a cut-off frequency of 5 Hz. This was performed using MATLAB™ gait analysis software (The MathWorks Inc., USA).

Frequency shifts for each epoch of EMG data were analysed using a fast Fourier transformation algorithm. The frequency spectrum analysis was restricted to frequencies in the range 5–500 Hz, as the EMG signal content outside of this range consists mostly of noise. The frequency spectrum from each epoch of data was compared with that from the first epoch, and the amount of spectral compression was estimated. This was performed using the technique described by Lowery et al. [15] as a modification of the work of LoConte and Merletti [16] and Merletti and LoConte [17]. The spectrum of the raw signal of each epoch was obtained and the normalised cumulative power at each frequency was calculated. The shift in each percentile frequency (i.e. at 0%…50%…100% of the total cumulative) was examined. The frequency shift was then estimated by calculating the mean shift in all percentile frequencies (MPFS) throughout the mid-frequency range, that is 5–500 Hz. This method is considered a more accurate estimate of spectral compression than median frequency analysis, which uses the value of a single (50th) percentile frequency only [15–17].

Corresponding data for torque, integrated EMG (IEMG), and percentile frequency were subsequently divided into 5×5 s epochs. The first included all data collected during the test from 0 to 5 s, the second all data from 20 to 25 s, the third from 45 to 50 s, the fourth from 70 to 75 s and the fifth from 95 to 100 s. Mean torques (Nm) and IEMG activity (mV), during each epoch were calculated. All data collected during the first epoch was described as 100% with all subsequent data from trial 2–5 normalised by using the first epoch as the denominator.

2.7. Statistics

All data are presented as mean±standard deviation (SD). An analysis of variance (ANOVA) was used to detect differences between groups for maximal data using STATISTICA analysis software (Version 6, Statsoft, Tulsa, OK, USA). Endurance data were analysed with a repeated measures ANOVA (trial×time). A Scheffe's post hoc test was used to detect differences between groups. Where a significant interaction between trial×time was calculated, a one way ANOVA was applied to determine the source of differences. Statistical significance was accepted when $P<0.05$.

3. Results

3.1. Maximal voluntary contractions

There were no significant differences between ISO, CON and ECC for maximal output during the MVC (177.2±61.1 Nm vs 169.2±41.1 Nm vs 211.1±63.1 Nm; ISO vs CON vs ECC) (Fig. 1).

Similarly, there were no significant differences between ISO, CON and ECC for maximal IEMG during the MVC (287.0±143.2 mV vs 305.0±146.3 mV vs 280.1±143.5 mV; ISO vs CON vs ECC) (Fig. 1).

MPFS ratios were calculated for the different contraction types. The ISO/CON and ISO/ECC ratios were significantly higher than CON/ECC ratio (1.101±0.086 vs 1.098±0.090 vs 0.997±0.052; ISO/CON vs ISO/ECC vs CON/ECC; $P<0.05$) (Fig. 2).

3.2. Endurance protocols

Normalised torque decreased signficantly ($P<0.05$) with respect to time for ISO and CON conditions, with final epoch values being 30.5±12.7 and 57.7±15.3% of initial values, respectively (Fig. 3). In contrast, during ECC endurance activity, subjects were able to maintain torque output for the duration of the 100 s, with final epoch values being 108.6±3.9% of the value achieved during the initial epoch.

As was the case with changes in torque output, the greatest reductions in IEMG were during ISO endurance contractions, with the final epoch being 37.7±12.9% of initial values (Fig. 3). In the CON and ECC group, however, IEMG was maintained thoughout the contraction. The ISO final epoch IEMG value was significantly less ($P<0.001$) than final CON and ECC values (Fig. 3).
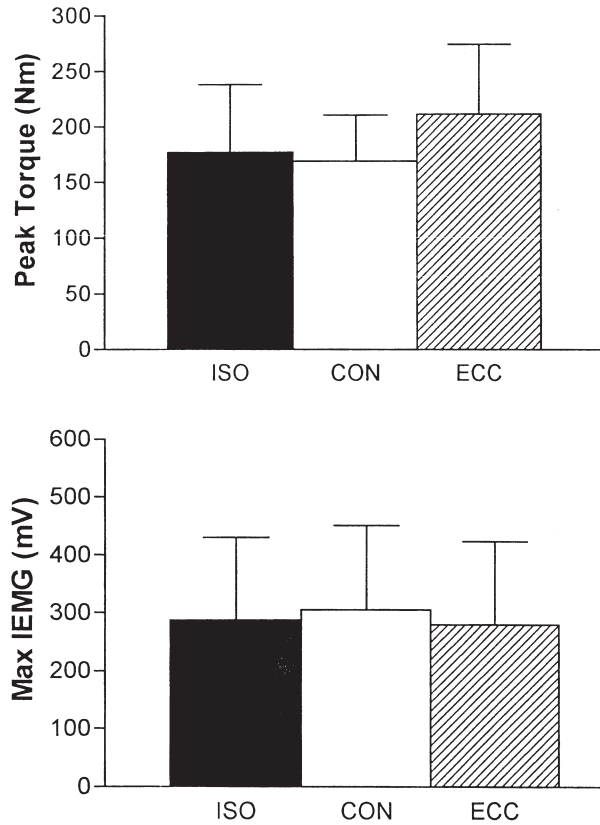
Fig. 1. Maximal torque output (Nm) and Maximal IEMG (mV) activity during maximal voluntary contraction for ISO, CON and ECC protocols (*n*=12). Values are mean±SD.
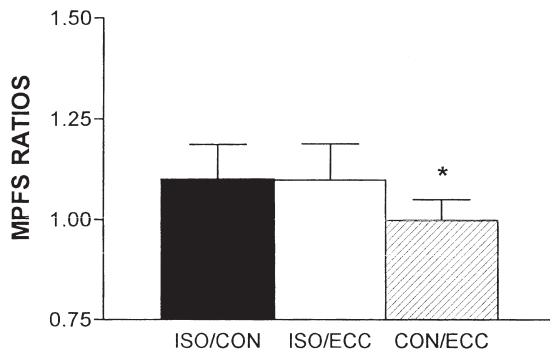

Fig. 2. Mean percentile frequency shift (MPFS) ratios for ISO, CON and ECC maximal voluntary contractions (*n*=12). Values are mean±SD (*P<0.05).

MPFS was compressed in all activity types (Fig. 3). This shift was most pronounced in the CON groups final epoch (69.2±9.6%) compared to ISO (72.6±9.4) and ECC (92.6±5.5%) groups. ECC final epoch MPFS was significantly higher than that in both ISO (*P*<0.01) and CON (*P*<0.01) groups.
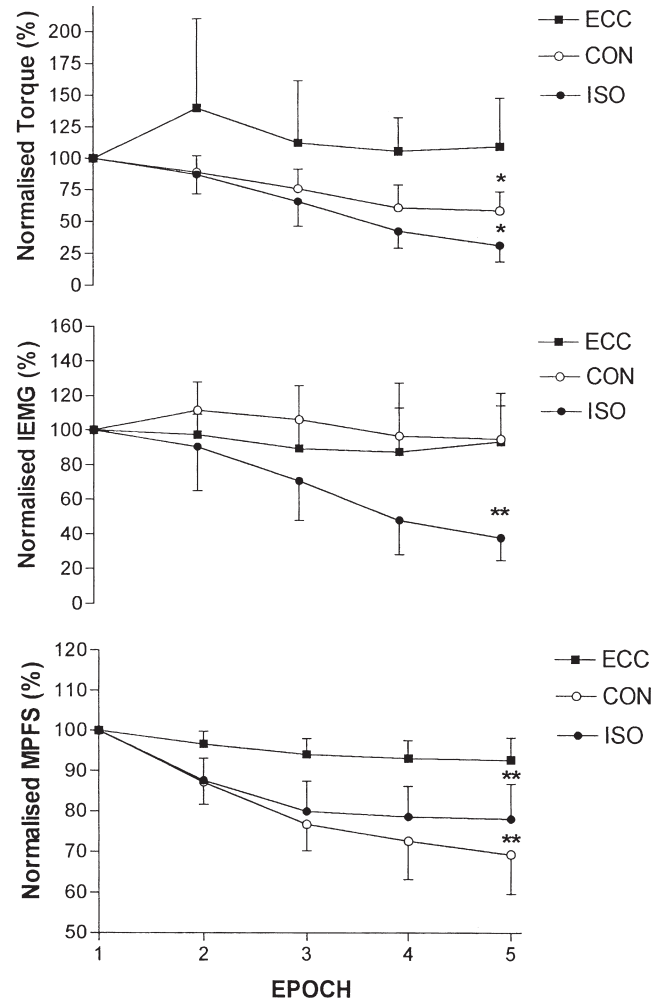

Fig. 3. Time normalised values for torque output, IEMG, and frequency spectrum ratios during a 100 s endurance trial for ISO, CON and ECC contractions (*n*=12) Values are mean±SD (*P<0.05; ** P<0.01).

4. Discussion

The main finding of this study was that neuromuscular fatigue profiles were different for isometric, concentric and eccentric muscle activities (Fig. 3).

4.1. Eccentric endurance protocol

During the eccentric protocol, the knee extensor muscles had a greater capacity to resist fatigue compared to isometric and concentric protocols. This result is similar to some [11,18] but not all [19] previous studies. Tesch et al. [11] found no decrease in eccentric force output, and Grabiner and Owings [18] described a 13% decrease in force output, which was also significantly less than the decrement in concentric activity found in their trial. In contrast, Komi and Rusko [19] found eccentric biceps activity at a speed of 40° s⁻¹ to cause considerable fatigue in the active muscles. However, the

protocol of these investigators allowed a 12 min rest between contractions, which may have contributed to the differences between findings in the different studies. It is possible that eccentric activities utilise additional mechanisms to generate force other than changes in frequency modulation or the recruitment of additional motor units. The elastic component of muscle and connective tissue may contribute to force production during eccentric activity [20], and this contribution may have attenuated the decrements in performance during repetitive eccentric muscle contractions.

It has been suggested that skeletal muscle is not fully activated during eccentric activity, as muscle stimulation produces even greater eccentric forces than can be generated consciously [11]. Incomplete motor unit activation during eccentric contractions would provide a greater reserve of fresh motor units during prolonged contractions allowing for enhanced cycling of motor units and lessened fatigue. This adaptation might explain the greater fatigue resistance of the rectus femoris muscle during the eccentric protocol compared to isometric and concentric protocols.

A marked compression of the EMG signal was observed for the isometric and concentric contractions, but not for the eccentric activity (Fig. 3). During submaximal contractions, it is possible to increase the motor command to counteract any reduction of force output in the recruited muscle fibres [5,21–23]. However, under the maximal conditions employed in this study, subjects cannot increase the magnitude of the motor command, thereby requiring alteration in neural firing frequency to attenuate declining force production. This is achieved by decreasing the conduction velocity of the neural signal, which compresses the frequency content of the EMG signal [5]. This decreased conduction velocity could maintain muscle force output by alteration of the recruitment pattern of the muscle fibres to select more fatigue resistant muscle fibres. The reason why MPFS changed little during eccentric compared to isometric and concentric activity may be due to the available motor unit reserve, as described previously. Eccentric contraction may be essentially submaximal in terms of motor unit recruitment. Therefore, under this condition subjects were able to modulate motor unit recruitment to maintain functional capacity without needing to modify nerve firing frequency components.

Moreover, EMG variables may be influenced by changes in muscle [24] and skin temperature [25]. Increased muscle temperature has been associated with elevated conduction velocity [4]. Petrofsky [24] found that increasing muscle temperature from 34 to 39°C was associated with a 4% reduction in the rectified IEMG signal, and a 20% increase in the median frequency. Eccentric activity generates more heat than concentric contractions for similar workloads [26,27]. It is possible therefore that increasing intramuscular temperatures

attenuated IEMG or frequency spectrum changes, particularly during eccentric activity. This temperature-dependent effect on frequency spectrum may have been responsible for the observed differences between ECC, ISO and CON activity types. Moreover, compression of the spectral signal may have been masked by the greater heat production that occurs during eccentric muscle action.

However, the combination of motor unit reserve and greater utilisation of mechanical/elastic energy is more likely to contribute to the fatigue resistant response of skeletal muscle during eccentric activity compared to the concentric and isometric conditions of our study.

EMG activity was only studied in the rectus femoris muscle, whereas force output of the entire knee extensor group was tested. There may have been changes in EMG activity of the other vasti muscles which were different to that found in this study. Further studies are needed to examine the EMG activity in all knee extensor muscles during eccentric activity.

4.2. Isometric endurance protocol

The isometric contractions demonstrated a profound reduction in torque in conjunction with decreased IEMG and compression of the frequency component. This combination of decreasing torque, IEMG and MPFS (Fig. 3) during the isometric protocol suggests that the neural drive is decreased [5]. It is not clear from this study whether this decreased neural drive is initiated by a pre-programmed central nervous system activity or is a response to afferent input changes resulting from metabolic perturbations in the peripheral muscles. Nevertheless, the decreased IEMG activity indicates that the efferent command signal is decreased during isometric fatiguing activity.

It has been proposed that the marked reduction in force output during ISO contractions results from ischaemia due to elevated intramuscular pressure or increasing concentrations of metabolites associated with fatigue, such as H^+, K^+, Pi [28] or NH_3 [29]. During sustained isometric contraction, the fatigue threshold corresponds with limitations in blood flow [30]. It is not clear from this study whether the afferent signal from any of these metabolic changes were related to the decreases in force output and efferent neural command changes.

A continuous isometric protocol was used for the trial, compared to the cyclical on–off activity tested during the eccentric and concentric protocols. Thus it was not possible in this study to assess whether the lack of rest periods during the isometric protocol contributed to the differences found in this study. Further studies should assess the extent of force output and neural drive changes which occur during intermittent isometric activity with similar rest periods to that which occur when testing concentric and eccentric activity.

4.3. Concentric endurance protocol

In contrast to the findings during isometric contractions, IEMG output during concentric contractions was maintained or increased, while force output decreased. This indicates that neural drive to peripheral muscle is maintained [7]. The results during dynamic contractions in this study were similar to those obtained by Tesch et al. [11], although contractions were slower in this study ($60°$ s^{-1} vs $180°$ s^{-1}).

It is not clear why concentric activity leads to different neural activation patterns compared to isometric activity. Fatigue is caused not only by a reduction in force, but also a slowing of contractile speed. Lewis and Fulco [31] have suggested that the use of isokinetic exercise involving a fixed contraction velocity, as occurs during isometric activity, prevents the investigation of changes in contractile speed. Most research of fatiguing voluntary contractions has concentrated on changes in force production, whereas it is likely that the development of fatigue is associated with combined changes in peak force output and peak shortening velocity [31,32].

The differences in efferent neural signals in concentric compared to isometric activity suggests that the process of muscle shortening or changes in muscle length may initiate an afferent signal different to that induced by isometric activity, and which results in increased rather than reduced efferent command during concentric activity. The finding that frequency content was also significantly greater during maximal isometric as opposed to maximal concentric and eccentric activity may also be related to muscle shortening as opposed to muscle isometric force output. This hypothesis requires further research.

4.4. Maximal force output

Maximal torque (Fig. 1) and IEMG (Fig. 2) were similar to that described in a previous investigation [11]. Eccentric torque tended to be greater than CON and ISO even though the IEMG values, and by implication the active muscle mass recruited, were lower during ECC than CON and ISO, utilizing less active muscle tissue as indicated by lower IEMG values. This may result from the elastic components of the skeletal muscles which may contribute to the force output during maximal eccentric ballistic activity, resulting in fewer muscle fibres producing a greater force output. MPFS was higher during isometric compared to both eccentric and concentric activity. This may be due to the static as opposed to dynamic nature of the different activities causing physiological differences in neuromuscular activity, or due to a relative change in the positioning of the EMG electrodes and of the muscle fibres generating the action potentials during dynamic contractions.

5. Conclusions

There are distinct neuromuscular fatigue profiles for isometric, concentric and eccentric contraction types. Under the conditions of this investigation, eccentric activity was largely fatigue resistant, while the isometric and concentric protocols displayed different neuromuscular fatigue profiles.

Acknowledgements

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Derek Kay received a BSc (Recreation and Human Movement) (Hons) in 1997 from Charles Sturt University, Australia. He is completing a PhD degree at the same university on the effect of fluid ingestion on cycling performance and fatigue development. He performed the research for this paper while on a learning sabbatical at the Unit of Exercise Science and Sports Medicine, University of Cape Town, South Africa in 1999.
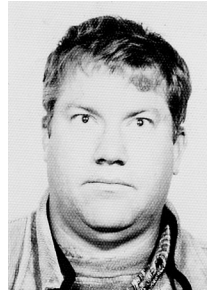
Alan St Clair Gibson received his MBChB degree from the University of Cape Town, South Africa in 1990. In 1991 and 1992 he performed his internship and a stint of general surgery at Edendale and Greys Hospital, South Africa. He received his PhD in 1997 from the University of Cape Town. In 1998 and 1999 he was an MRC postdoctoral fellow in the Unit of Exercise Science and Sports Medicine, University of Cape Town, and in 2000 was appointed a senior researcher in the same unit. He is currently completing a medical doctorate in neuromuscular changes associated with ageing, and his research interest is neurobiology and system control mechanisms.

Martin J. Mitchell received his MBChB in 1999 from the University of Aberdeen, Scotland, and is currently involved in internship and medical rotations in Scotland and England. He performed this research as part of a student training visit to the Unit of Exercise Science and Sports Medicine, University of Cape Town.
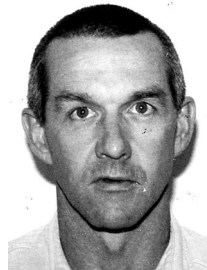
Mike I. Lambert received his Bsc (Agric) in Animal Science from the University of Natal, South Africa in 1978. He received his BA (Phys Ed) (Hons) from the University of Rhodes, South Africa in 1982, and his MSc in Physiology from University of South Carolina, USA in 1984. He received his PhD from the University of Cape Town, South Africa in 1990. From 1990 to 1998 he was a senior lecturer and from 1998 to 2000 an associate professor in the Unit of Exercise Science and Sports Medicine, University of Cape Town, South Africa. His research included neuromuscular performance, muscle physiology and the limits to exercise performance. He has a number of paper published in international journals, is on a number of journal editorial boards, and is the Director of the High Performance Laboratory of the Sport Science Institute of South Africa.
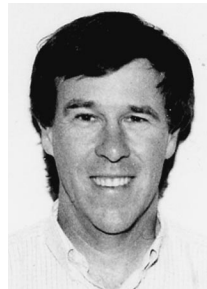
Timothy D. Noakes received his MBChB in 1974 from the University of Cape Town, South Africa. After completing his medical internship, he received his MD in cardiac physiology from the University of Cape Town. He was an MRC Research Fellow from 1976 to 1980, and a lecturer and associate professor from 1981 to 1989. In 1990 he was made full professor and head of the Unit of Exercise Science and Sports Medicine, University of Cape Town. His research interests include the limits to maximal performance in exercise, and clinical problems in sports medicine. He has published over 200 publications in international journals, is on a number of journal editorial boards, has received numerous awards, and is recognized as a world authority in the fields of Exercise Science and Sports Medicine.