Sports Eng (2009) 11:207–209
DOI 10.1007/s12283-009-0024-5

SHORT COMMUNICATION

Is stroke smoothness a reliable indicator of fatigue in ergometer rowing?

Nicholas Caplan · Trevor N. Gardner

Published online: 13 August 2009

Abstract A measure of stroke smoothness (SS) has been presented previously to indicate the degree to which rowers produce an "ideal" handle force profile that of the positive half of a sine wave [2]. This study aimed to determine the influence of fatigue on SS. Ten male rowers completed a maximal intensity trial. Fast Fourier transform methods were used to calculate SS which was given by the amplitude of the fundamental frequency as a percentage of the sum of the first ten peaks. Visual inspection of the data showed indications of a reduction in movement coordination as a function of fatigue. However, SS did not change significantly between the first, middle and last ten strokes ($p = 0.205$), despite a 21% reduction in mean power between the start and end of the trial. The results suggested that although the shape of the force profile can qualitatively indicate a reduction in movement coordination, the smoothness of the force profiles remains similar with fatigue.

Keywords Fourier analysis · Biomechanics · Sport · Kinetics · Rowing · Fatigue

1 Introduction

The application of force by the rower to the oar handle is of great importance for the maintenance of a high mean boat velocity, which has been suggested to be a key determinant of race time [1]. Smith and Spinks [2] suggested that the theoretically ideal pattern of force exerted at the handle should follow the positive half of a sine wave in order to ensure efficient production of propulsive force. Most rowers show force–time curves which deviate from this ideal profile, however, and these deviations have been attributed in the literature to poor sequencing and coordination between the major muscle groups used during the drive phase, resulting in a non-smooth transition between leg, trunk and arm movements [2–6]. It has also been attributed to muscle fatigability [7].

Smith and Spinks [2] attempted to quantitatively assess the fundamental frequency characteristics of this force–time curve, determining the "smoothness" of the stroke during the drive phase using a numerical method. The less smooth a force profile at the handle, the further the deviation away from the ideal curve, and the lower the calculated smoothness of the stroke. Mean stroke smoothness was determined for the entire duration of a 6 min rowing ergometer trial. However, this ignored any effects of fatigue, which have been suggested to influence the coordination of body segments [8], thus affecting performance.

The purpose of the present study was to determine the influence of fatigue on stroke smoothness in ergometer rowing, and to examine whether this biomechanical measure is sufficiently sensitive to within-subject technique changes due to fatigue.

2 Methods

Ten male university level rowers participated in the study, having a mean age, height and mass of 20.6 (±1.6) years, 1.82 (±0.06) m and 80 (±8.7) kg, respectively. Subjects

N. Caplan (✉)
Biomechanics Research Unit, School of Psychology and Sport Sciences, Northumbria University, Northumberland Building, Newcastle upon Tyne NE1 8ST, UK
e-mail: nick.caplan@northumbria.ac.uk

T. N. Gardner
School of Sport and Exercise Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

gave written informed consent, and ethical approval was granted by the local ethics subcommittee. Subjects had 2.3 (±1.8) years experience at competitive rowing and were a combination of lightweights and heavyweights.

After a suitable warm-up, subjects performed a 3 min 30 s maximal intensity trial at a stroke rate of 30 strokes min^{-1} on a Concept 2 rowing ergometer (model C) with the flywheel resistance set to 4 (drag factor = 1.25×10^{-4} N m s^2). Handle force was measured using a 5,000 N load cell (F256, Novatech Measurements Ltd., UK) connected in series with the ergometer chain. The load cell had a stated linearity and hysteresis both of 0.05%. Data were sampled at 50 Hz by an analogue–digital card (KPCI-3101, Keithley Instruments, USA) and stored in a computer for later analysis. Handle velocity, which was also sampled at 50 Hz, was calculated by measuring the rotational velocity of the chain sprocket axle (diameter 2.83 cm) of the ergometer by a DC tachometer (263-6005, RS Components, UK) to a resolution of 0.07%. The handle velocity was positive during the drive phase and negative during the recovery phase. The catch and finish were thus defined as the points at which handle velocity changed sign.

Stroke smoothness was calculated using a fast Fourier transform (FFT) analysis of the force data. Before applying the fast FFT, following the method of Smith and Spinks [2], the raw force data were time-normalised to 32 data points for the drive phase of each stroke, using a cubic spline interpolation. One full cycle of the data for the analysis was recalculated by taking the first 16 data points and adding its mirror image in front of the catch, and taking the second 16 data points and adding its mirror image to the end of the drive phase. This provided a total of 64 data points for one full cycle to which the FFT was applied. The stroke smoothness of each stroke was then defined as the amplitude of the fundamental frequency peak of the frequency power spectrum as a percentage of the total sum of the amplitudes of the first ten frequency peaks.

Smith and Spinks [2] presented their force profiles, being determined with respect to the oar shaft angular displacement and compared to handle linear displacement in ergometer rowing. However, the use of time-normalised force profiles when determining stroke smoothness negates the influence of handle position during the stroke and the inherent differences between the two rowing forms.

Each trial contained approximately 105 strokes. The first five strokes were discarded as they were assumed to be the period in which the flywheel acceleration took place. Three analysis periods were then extracted: the first ten strokes, the middle ten strokes and the last ten strokes. A one-way analysis of variance with repeated measures, post hoc Tukey, was used to determine if there was a significant interaction between analysis periods for both mean power and stroke smoothness for all subjects. A 95% confidence level was used throughout.

3 Results

Average power per stroke during the first and last 10-stroke periods indicated that fatigue led to a significant reduction in power output over the trial period ($F_{2,267} = 86.167$, $p < 0.05$), as shown by a 21% reduction between these two periods, from 710 (±11) to 564 (±8) W.

Example force data are shown in Fig. 1 comparing an un-fatigued stroke to a fatigued stroke for a representative rower. Visual inspection of the data revealed that the shape of the force profiles differed, accompanied by a lower peak force in the fatigued stroke.

Figure 2 shows example FFT outputs for two participants: one with the highest stroke smoothness and the other with the lowest stroke smoothness. For each participant a fresh and a fatigued stroke FFT are shown. Although stroke

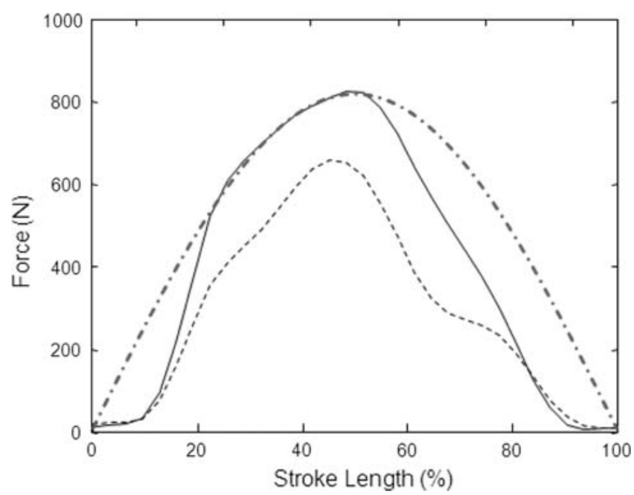

Fig. 1 Example fresh (*solid line*) and fatigued (*dashed line*) force–time curves for a representative subject. The theoretically ideal force time profile (positive half of a sine wave) is also shown for the fresh stroke (*dash dotted line*)

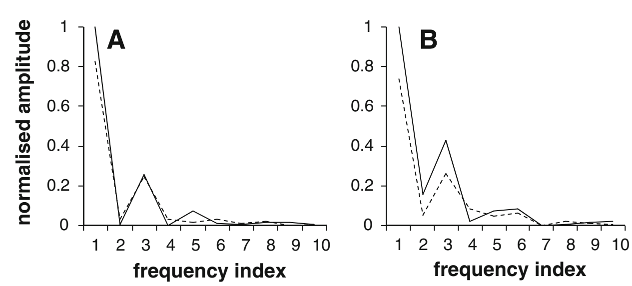

Fig. 2 Example FFT outputs are shown for a fresh (*solid line*) and fatigued (*dashed line*) stroke for (**a**) a participant with higher stroke smoothness and (**b**) a participant with lower stroke smoothness

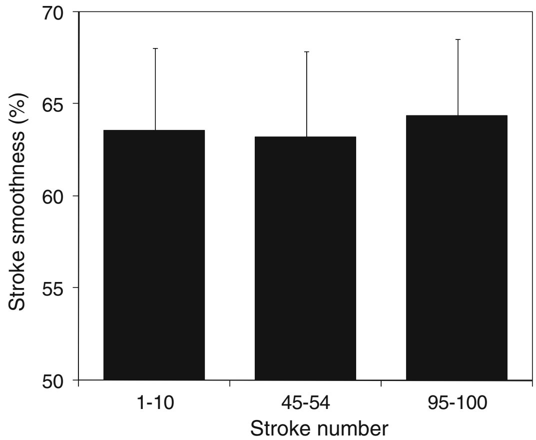

Fig. 3 Mean (±SD) stroke smoothness is shown for all subjects in each of the three analysis periods

smoothness ranged as much as 18% between participants, no significant differences were observed between the three 10-stroke periods ($F_{2,267} = 1.592$, $p = 0.205$, Fig. 3). The differences between stroke periods resulted in trivial effect sizes between the start and middle periods (ES = 0.08), and the start and end periods (ES = 0.18). A small effect size (ES = 0.26) was found between the middle and end stroke periods.

4 Discussion

The purpose of this investigation was to determine the influence of fatigue on stroke smoothness in ergometer rowing, and to determine whether this measure is sufficiently sensitive to expose any within-subject variability between strokes due to a reduction in body segment coordination through the drive phase of the rowing stroke.

Visual observation of the force profiles as shown in Fig. 1 suggested that the force profile deviated away from the ideal profile with fatigue. These changes in the shape of this curve have previously been attributed to poor synchronisation of body segments [8]. However, stroke smoothness was shown not to differentiate between fresh and fatigued force profiles, and hence was not sensitive to within-subject variability in the force profile shape between strokes seen as a result of fatigue. No significant differences in stroke smoothness were observed between any of the analysis periods.

Wing and Woodburn [9] suggested that rowers maintained the shape of their force–time curve with fatigue despite a reduction in peak force. Although visual observation of the differences seen between fresh and fatigued force profiles in the present study highlighted clear differences due to fatigue, the lack of significant change in stroke smoothness appears to support the suggestions of Wing and Woodburn [9], that the force profile frequency characteristics remained unchanged. It appears that although qualitative assessment of the shape of the force profiles suggested that they changed with fatigue, as illustrated in Fig. 1, the fundamental frequency characteristics of the force profile were not altered, resulting in the non-significant differences in stroke smoothness seen here.

5 Conclusion

In conclusion, it has been demonstrated that although stroke smoothness has been shown previously to discriminate between rowers of different abilities [2], it is unable to detect within-subject variability induced by fatigue. The lack of significant difference in stroke smoothness with fatigue also supported the notion that the fundamental frequency characteristics of the force profile is not significantly changed by fatigue, but simply that the force is reduced in magnitude. Further research is warranted to determine an appropriate method of quantitatively assessing changes to the force profile with fatigue in order to allow coaches to differentiate between rowers who are able to maintain posture with fatigue and those whose posture deteriorates.

References

1. Schneider E, Angst F, Brandt JD (1978) Biomechanics in rowing. In: Asmussen E, Jørgensen K (eds) Biomechanics VI-B. University Park Press, Baltimore, pp 115–119
2. Smith RM, Spinks WL (1995) Discriminant analysis of biomechanical differences between novice, good and elite rowers. J Sports Sci 13:377–385
3. Christov R, Ivanov S, Christov R (1996) Problems with the biomechanical analysis of the rowing technique in real and test conditions. In: Tsarouchas L, Terauds J, Gowitzke BA, Holt LE (eds) Biomechanics in sports V. Hellenic Sports Research Institute, Athens, pp 269–275
4. Duchesnes CJ, Borres R, Lewill L, Riethmuller M, Olivari D (1996) New approach for boat motion analysis in rowing. In: Tsarouchas L, Terauds J, Gowitzke BA, Holt LE (eds) Biomechanics in sports V. Hellenic Sports Research Institute, Athens, pp 276–280
5. Mason BR, Shakespear P, Doherty P (1998) The use of biomechanical analysis in rowing to monitor the effect of training. Excel 4:11–47
6. Struble KR, Erdman AG, Stoner LJ (1981) Computer-aided kinematic analysis of rowing. In: Morecki A, Fidelus K, Kedzior K, Wit A (eds) Biomechanics VII-B. University Park Press, Baltimore, pp 425–429
7. Torres-Moreno R, Tanaka C, Penney KL (2000) Joint excursion, handle velocity, and applied force: a biomechanical analysis of ergonometric rowing. Int J Sports Med 21:41–44
8. Holt PJE, Bull AMJ, Cashman PMM, McGregor AH (2003) Kinematics of spinal motion during prolonged rowing. Int J Sports Med 24:597–602
9. Wing AM, Woodburn C (1995) The coordination and consistency of rowers in a racing eight. J Sports Sci 13:187–197