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FES Rowing Biomechanics: fixed and floating stretcher ergometers

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Abstract

Cardiovascular disease and osteoporosis result in reduced life expectancy and low energy fractures in SCI. In the future, new cellular treatments are anticipated that aim to restore neurological function; however, these are only likely to be of benefit to either the recently injured or to those who have avoided irreversible secondary conditions such as CVD and osteoporosis. FES rowing potentially offers significant cardiovascular health benefits. Here preliminary results are presented, using two forms of FES. Joint contact forces are presented for a T4 (ASIA A, 11yrs post injury) 72.5kg male with 9 yrs of daily FES rowing experience. Peak joint contact forces at the knee (but not the hip, ankle or foot) were in excess of 1.5× body weight (BW) at stroke rates approx 30 cycles/min, with over 7200 loading cycles per month. This pattern of usage is expected to provide significant cardiovascular health benefits as well as preserve bone mineral around the knee- which is a common fracture site. Joint contact forces up to 4 times BW were observed depending on rowing technique. Thus there is an increased risk of fracture. Although we have not observed any fractures so far, it is now required to determine safe training protocols for FES rowing.

Keywords: *www.FES rowing.org, 3D biomechanics, floating stretcher ergometer, osteoporosis, fracture risk in SCI.*

Introduction

FES Rowing is a recently developed form of sport and hybrid physical exercise for people with spinal cord injury [1-5] resulting in higher levels of work output, increased cardiovascular fitness and cardiac adaptation [6]. Two of our FES rowers, Robert Holliday and Tom Aggar, have used FES rowing to train for elite level Adaptive Rowing - achieving Gold in the World Championships and Olympic Games. Other collaborating groups using the system have also demonstrated significant cardio-vascular health benefits [7].

The USA Model Spinal Cord Injury System report fracture incidences due to osteoporosis of 14% at 5 years, 28% at 10 years, and 39% at 15 years post injury, based on outpatient studies, and a prevalence of 25-46%. The causes of fractures are often unknown or are associated with relatively low energy trauma. These fractures have an associated 78% increase in mortality risk [16]. The pattern of limb loading is generally accepted as a major factor in determining BMD as illustrated by the Stanford bone mineral density index (BDI) BDI = $(n.[\beta.\text{GRF}]^m)^{1/(2m)}$ where $\boldsymbol{n}$ is the number of loadings per day, $\boldsymbol{\beta}$ is a subject-specific scale factor accounting for differences in body weight (BW), $\boldsymbol{m}$ is an empirical exponent that can be thought of as weighting factor for the relative importance of load magnitude and the number of daily loading cycles [8]. Dudley-Javoroski & Shields [9,14] determined that FES ankle plantarflexion contractions (30 contractions per min with about 8,000 per month for 3yrs) resulted in compressive loads above 1 to 1.5 times BW were required to attenuate BMD loss in SCI.

Normal ergometer rowing can produce lower limb joint contact forces of 5, 7 and 8 times body weight (BW) for the ankle, knee and hip joints respectively [10]. Here we present preliminary results from a biomechanical study, in particular the results of an experienced able-bodied rower and a FES rower. The rowing machines used were either the standard Concept 2 model (D) or the Concept2-Dynamic http://concept2.co.uk/dynamic/

The C2-Dynamic is a type of floating stretcher system principle that may closer approximate conditions on-water [11].

Materials and Methods

Data is presented here for two participants. The co-author RG (57 yrs, 75 kg male, 1.72m height with a T4 ASIA (A) 11 years previously. RG started FES rowing in 2003 and has maintained 2-3, 30 min session per week since then. The able-bodied male rower was 24ys, 82kg, 1.81m height. In both cases, following an initial 10 minute warm-up the rowers were asked to row as hard as they could for approximately 20 strokes. Rowing tests on both ergometers were conducted on separate days approximately 3 weeks apart.

The ergometers were adapted for FES using a seat with a fixed backrest and seat inclined 15^o rearwards. A harness was used to stabilise and restrain the trunk (Bodypoint Inc, USA). Telescopic leg stabilizers were used to maintain a sagittal plane motion. Pals+ skin electrodes were positioned to stimulate bi-laterally the quadriceps (ext vasti) for extension during “drive” and the hamstrings to flex the knee during the “recovery” phase. A 4-channel stimulator (Odstock Medical Ltd, UK, (monophasic pulses at 50Hz and 250µs pulse width with the amplitude adjustable 0-115mA) was adapted for use with an external control switch attached to the ergometer handle. When pressed electrical stimulus was applied to quadriceps and when released the stimulus was immediately applied to the hamstrings. The subject RG employs an anticipatory strategy in which each rowing cycle is controlled by pressing and releasing the switch with a remarkably small variation in timing approximately +/- 30ms [12]. The track of the C2-model(D) was inclined to the horizontal by1.9 degrees for able bodied use and by 3.8 degrees for FES rowing. A bungee cord was used with the C2-Dynamic to connect the seat and stretcher to assist recovery (stiffness 500N/m, pretension 78N).

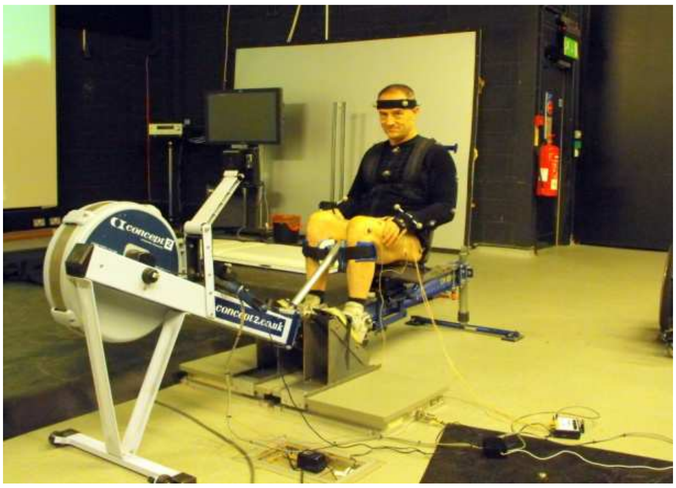
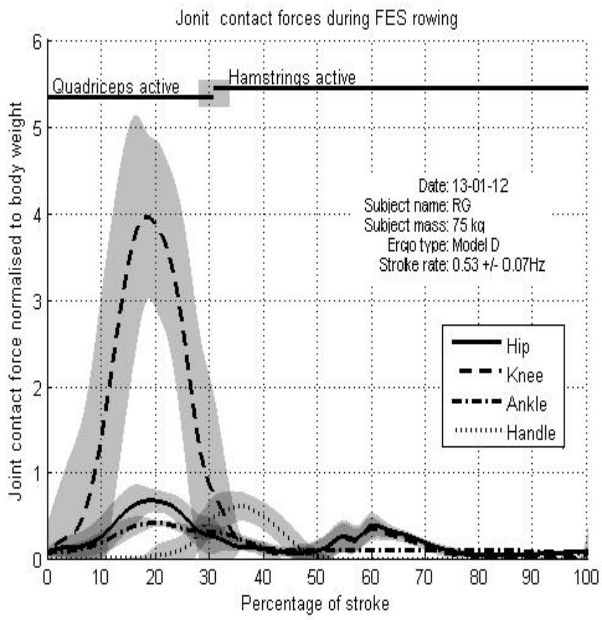


Fig. 1: RSG prepared for FES rowing on the adapted C2-model(D).

Fig. 2: Subject RG using the adapted C2-Dynamic

Handle forces were measured using a strain gauged transducer in-line with the handle. On the C2-model(D) the foot stretchers were replaced by brackets attached to two, floor mounted, AMTI force plates as shown in Figure 1. A 12 camera Vicon system was used to measure the position of 37 retro-reflective markers from which joint angles, the angular velocities and angular accelerations were calculated. These were then used to drive the motion of a musculo-skeletal model [13] which enabled the calculation of the muscular loading distribution. From a consideration of the loads in the muscles crossing the joints, together with external forces and inertial loads the joint contact forces were derived.

Results



(a)

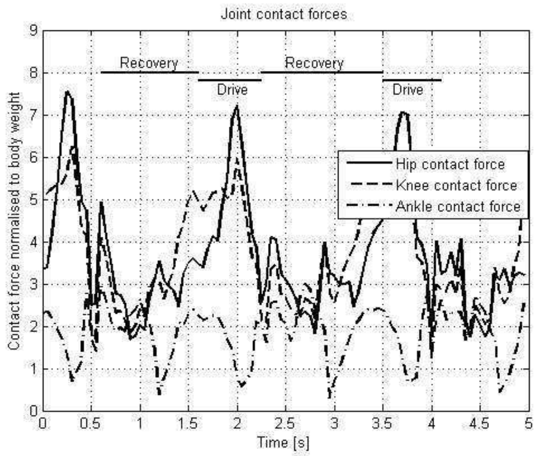


Fig. 3: FES Rowing C2-model(D) Joint contact forces for the hip knee and ankle joints: (a) SCI rowing; (b) able-bodied expert rowing.

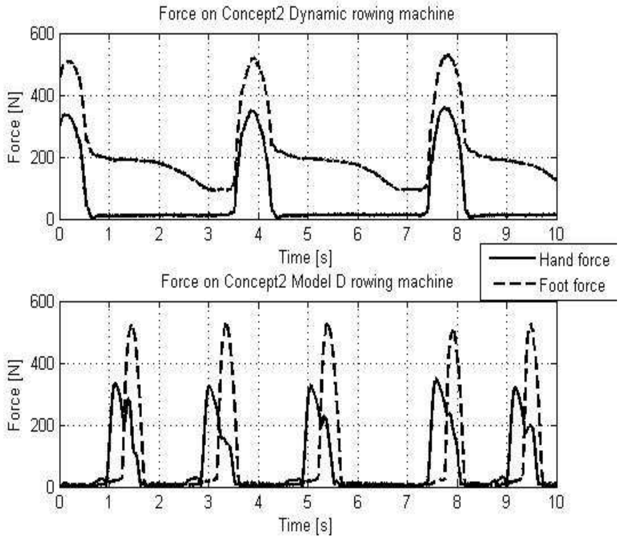


Fig. 4: FES Rowing Handle and Foot forces for the C2-model(D) (lower trace) and for the C2-Dynamic upper trace.

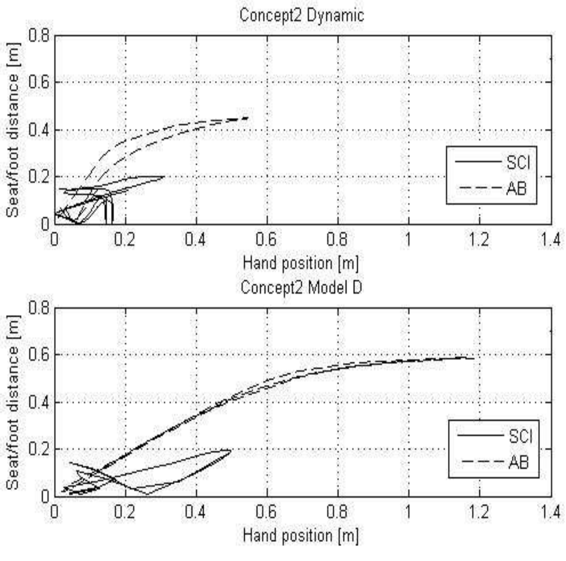


Fig. 5: Sample kinematics. The SCI subject adopted a different rowing style for each ergometer.

Discussion

Kinetics Figure 3 (b) confirms the levels of joint contact forces for expert rowers as reported in [10]. Figure 3(a) indicates for FES rowing the maximum joint contact forces at the hip, knee and ankle were approx 0.75, 4 and 0.4 times BW. Thus only the knee forces exceed the threshold of 1.5 × BW necessary to prevent bone mineral loss [14]. This is clinically significant since most fractures occur just above the knee [14]. The hip and ankle forces were sub-threshold, presumably because no muscles were FES activated across those joints. These forces are significantly higher than those previously reported for FES rowing (simulated by able-bodied subjects) of 1.47, 0.4 and 0.6 times BW [15].

Figure 4 indicates that the forces recorded at the handle and foot during FES rowing on the C2-Dynamic were similar to those on the C2-model(D). Both rowing ergometers induce similar joint contact forces. The slower stroke rate of the C2-Dynamic was associated with increased spasticity during that session and not the ergometer.

Kinematics FES rowing is less than half the stroke length than that of the able bodied rower on the C2-model(D) and is associated with the fixed backrest preventing trunk swing. The shape of the able bodied traces on both machines suggests that a similar style of rowing with strong coupling between the upper and lower limbs where the handle and foot displacements increase and decrease monotonically with no reversal on handle or seat motion during both the drive and recovery phases.

The FES rower adopted two distinctly different styles that clearly differ from normal ergometer rowing. *Style (1)* In the case of the Concept 2 Model(D); an extra rapid pull was applied to the handle during recovery causing arm flexion, to assist the return to catch, and the force peak that precedes the foot force in Figure 4. *Style (2)* In the case of the Concept 2 Dynamic; the handle and foot forces overlap and the foot force is maintained throughout drive as the SCI subject deliberately maintained quadriceps stimulus until his legs fully extended before switching over the stimulus from quadriceps to hamstrings to start recovery i.e. there was no pull on the handle during recovery.

Conclusions These results suggest that FES rowing, with either stretcher system can induce significant musculo-skeletal force actions has a potential role in preventing osteoporosis at least around the knee joint, which a common site for low trauma fractures. Thus there is a fracture risk and caution is advised.

Further work is required to more optimally distribute supra-threshold force actions throughout the lower limbs to preserve trabecular architecture as well as, tendon and ligament health. This will be essential if the future goal of locomotion is to be achieved by either new FES or cellular treatments.

There is also an urgent need to development fracture risk and bone strength assessment tools as well as safe progressive loading protocols to optimize the clinical translation of FES rowing.

There appear to be various possible FES rowing styles on the different types of rowing ergometer, further work is required to optimize the rowing style and associated FES control system for safe bone loading.

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