Sensor node acceleration signatures and electromyography in synchronisation and sequencing analysis in sports: a rowing perspective

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Abstract

Following a review of the key determinants of successful rowing, a wireless body sensor network (BSN) was developed to monitor boat and body segment acceleration, and surface electromyography in major muscles recruited during the rowing stroke cycle. Its design was optimised to yield maximum information about the rowing stroke cycle from fewest sensors, and minimise the power consumption of the nodes. The system was validated against the Qualisys motion capture and high speed camera system with most Pearson correlation coefficients in excess of r=0.8.

On land ergometer experimentation allowed muscle recruitment over the stroke cycle to be studied, with multiple experiments combined using correlation of the acceleration signatures of back and thigh nodes (r=0.95). It was demonstrated that it was possible to identify one of the common rowing errors of “shooting-the-slide” from the data collected, and that a marked decrease in correlation of good-to-bad technique over the drive phase of the stroke (0.95 reducing to 0.34 in the experiment undertaken) could be used to indicate the presence of this error.

Extension of the wireless BSN to encompass boat and two oarsmen was demonstrated, allowing correlation of their rowing signatures to be studied, indicating their cohesion as a crew.

Keywords

Rowing, acceleration, electromyography, sequencing, synchronisation

Introduction

Understanding the factors which can influence sporting performance and allow identification both of promising sporting candidates and to coach them to reach maximum potential is vital to success [1]. Miniaturisation and integration of sensors and electronics has facilitated the observation and analysis process allowing multiple variables, including body kinematics and biometrics, to be scrutinised to determine their effect upon performance. Furthermore, the adoption of wireless sensor networks (WSN) allows for greater flexibility in the collection of data, leaving the athlete unencumbered by wires, moving beyond simply the idea of telemetering (transmitting the data to a remote datalogger), to the collection and exploitation of data from multiple unconnected sensors [2]. Such advances lead to greater monitoring in the natural environment of the sport, thus removing the limitations and influences of laboratory measurement, and allowing for the capture of metrics that cannot be determined by the more traditional video analysis methods [3].

The choice and location of sensors is dependent upon what analyses are desired, and thus determined by the sport itself, and the factors and metrics that indicate or influence success and achievement in that sport. An excellent example with which to demonstrate the benefits of Body WSNs is Rowing. This includes many of the characteristics for which synchronous and wireless measurement at multiple sites benefits; an all body sport requiring specific sequencing of limb involvement, a cyclic action, a natural environment that does not facilitate observation and analysis, and that cannot accurately be mimicked on dry land, and (in multi-oarsman boats) a requirement for synchrony within the crew.

This study identifies sensors and node placement that allows the study of the stroke cycle in rowing, both on land ergometers and in-boat, enabling the optimisation of the rowing stroke to yield an improvement in performance. Through the use of an acceleration signature to identify the stroke cycle, and muscle activity measurement, variance in the rowing stroke from recognised good technique can be highlighted, with a view to providing feedback to the oarsman.

Key determinants of successful rowing

The time taken to row a set distance is clearly the key determinant of successful rowing, leading to boat velocity (for a given boat type) being the gold standard [4]. However this reveals nothing about the technique or physiology of the oarsman, and where improvements might be made. Boat velocity is not constant, and varies over the stroke cycle [5], and thus manner and degree with which the boat velocity varies over the course of a stroke will affect the final boat velocity. Minimising this variation will minimise drag on the hull of the boat [6], and ultimately minimise the energy expenditure of the oarsmen [7]. What causes this variation in velocity over the stroke cycle is the biomechanics [8], timing [9] and balance [10] of the oarsman, all of which affect the run of the boat and the water drag.

Maximum force application towards the velocity production of the boat is achieved through timing and sequencing of the power application to overcome boat drag forces [6]. The measurement of force has been undertaken by a number of researchers at different locations upon the boat: oar force, both at pin (where the oar engages with the boat) and oar handle, and foot stretcher force [11, 12], whilst others have attempted to analyse forces at the spoon of the oar [13, 14]. Such analyses have led to opposing views with regard to the importance of the catch and finish of the rowing stroke in the generation of maximum boat velocity. Kleshnev states that hydrodynamic lift forces of the spoon (at the catch) contributes greater propulsive force (56% compared to 44%) than that of drag forces (which the oarsman levers against when the oar is perpendicular to the boat). However transverse forces, greatest at the catch and finish, produce a yaw affect which can detrimentally affect the balance and velocity of the boat [11].

The sequencing of force application within the stroke cycle thus goes beyond the ratio of drive (oar spoon in the water) and recovery, leading to the naming of four accepted rowing styles: Rosenberg, Grinko, DDR and Adam [15], the first two being of a sequential style, the latter two a simultaneous approach. No consensus has yet been agreed on the preferred approach, with Kleshnev concluding that the sequential style results in greater power, and the simultaneous approach being more biomechanically efficient. In more recent research, Kleshnev indicates the importance of analysing the muscle contributions of the oarsman [16]. Such body centric measurements are also important to show the different physiological effects of the different rowing styles [17], with blood lactic acid concentration and VO2 measurements in oarsmen with different rowing styles indicating elevated levels of both in those with a steeper power increase at the beginning of the stroke. Further on-body analysis has been used to analyse the rowing stroke with a view to greater understanding and prevention of injury [18].

Finally, extension of on-body measurement to include multiple oarsmen (a crew) and the boat itself should yield greater information about sequencing and performance correlations [19, 20]. Monitoring the synchronisation of limb sequencing and force application, in conjunction with boat performance might ultimately yield to a tangible measure for the "swing" effect, described by US Rowing Nomenclature as "a hard-to-define feeling when near-perfect synchronisation of movement occurs in a shell, enhancing the performance and speed of the crew" [21].

Method

A rationale of minimising the number of sensors per node whilst maximising potential information collection, and common functionality throughout the network was taken to allow for greatest flexibility of placement of the nodes with minimal set-up and calibration on-body. Emphasis was also placed upon minimising power requirements, through minimising the ON time of the wireless module, notably the transmit time of data from slave nodes to the coordinator. Both these approaches minimise node size – an important factor with nodes placed upon the body.

Sensor choice, node placement rationale

Instrumentation upon the boat to measure oar and stretcher force, oar angle and boat acceleration have been staples of rowing stroke analysis for some time [13, 22], and attempts have also been made to study body segment acceleration and velocity, notably by Kleshnev who used this to study what he describes as the micro-phases of the rowing stroke cycle [23], and the sequenced application of work by legs, trunk and arms, though these measurements were made by unwieldy cable position transducers.

Micro-electro-mechanical systems (MEMS) accelerometers (measuring linear acceleration and vibration) and gyroscopes (measuring angular velocity) have become increasingly popular in handheld and wearable devices for the purposes of gesture, movement and positional information due to their small size and low power. More recently inertial measurement units (IMUs) combine these in one sealed and calibrated package, often with additional magnetometers (magnetic field sensor) to potentially deliver up to six degrees of freedom (DOF) positional information (three degrees translational, three degrees rotational). The fusion of up to nine IMU data inputs yields greater accuracy, though this brings with it complex processing and until very recently a hefty price-tag, but show promise for the future.

Current literature in rowing and wider sporting and health monitoring fields demonstrate increasing research exploiting MEMS technology. Early on-body accelerometer research employed single-axis accelerometers for body posture identification [24]. Subsequent research combined information from integrated MEMS tri-axial accelerometers and gyroscopes to yield an estimate of limb orientation [25, 26] and joint angle [27-29]. These latter groups additionally applied anatomical constraints of the joint (e.g. the knee) to further improve the estimation. In rowing, accelerometers and gyroscopes have been used both in wired systems upon the boat and oars [30] to determine stroke rate and drive-to-recovery ratio, and wirelessly upon the body during ergometer rowing in the laboratory [31] to analyse rotation in the lower back and femur to study the relation to back injury. A couple of groups, both within and outside the study of rowing, have used solely multi-axis accelerometers in novel physical arrangements to determine rotation and translation through computation [32, 33], thus demonstrating the possibility of determining angular displacement without the zero drift errors of gyroscopic techniques.

Another on-body measurement that would allow analysis of the application of force, and specifically limb sequencing in rowing is that of surface Electromyography (sEMG), and in an article in 2010, Kleshnev makes a departure from his discussions of boat kinetics and kinematics of rowing to consider biomechanical analysis through EMG, publishing a pilot study looking at the sequencing of muscle activation during the rowing stroke [16]. Some earlier studies had taken place, often analysing asymmetry in muscle recruitment in rowing [34, 35], but subsequently to Kleshnev's article a number of studies have employed sEMG data loggers (wired devices that allow multiple muscles to be monitored) to monitor rowing [36-41], often comparing rowing ergometer rowing and on-water rowing.

Combining the flexibility and potential of MEMS sensors with the biomechanical possibilities of sEMG allows their combined data to yield information on sequencing of the rowing stroke, and synchronicity of a rowing crew. With a view to keeping dataset size and computation at a minimum for purposes of node optimisation, it was determined that tri-axial accelerometers would be employed upon the wireless nodes, thus also affording the possibility of a hull-mounted node to measure the acceleration of the boat itself.

Initial experimentation was performed upon a rowing ergometer to determine the optimum minimum placement of the nodes that would allow both an acceleration 'signature' of the node site to be captured, to be used for the identification of the stroke cycle, and measurement of a pertinent muscle. Whilst a large number of node placements were used over the course of experimentation, allowing the measurement of many muscles, a minimum measurement of thigh acceleration with biceps femoris sEMG, and upper back acceleration with trapezius sEMG were chosen to illustrate the rowing stroke. Monitoring acceleration at the thigh and the upper back allows an acceleration signature to be captured at two sites which can best inform upon the phases of the rowing stroke regardless of which of the four accepted rowing styles was adopted by the oarsman. Additionally, since acceleration measured upon an oarsman in-boat takes place within an accelerated system [42], the signature is different upon a rowing ergometer than in-boat. However, the measured signature at these two sites yields nevertheless a defined shape that allows the transition of one stroke to the next to be identified. The influence of boat acceleration upon oarsmen within the same boat is equal.

Connection between sEMG electrode sites and the node itself were kept short to minimise cable movement artefacts [43], but whilst still allowing the electrodes to be placed slightly distant from the node itself. This allowed for example a single node position to measure both biceps and rectus femoris muscles of the thigh.

System optimisation

System optimisation can be performed both at the hardware design stage and in the firmware. A Microchip PIC microcontroller with extreme low power functionality was used within the node architecture providing space-saving on-chip peripherals (sensor data digitisation, timers, on-board memory, etc). Whilst the MEMS accelerometers require minimal external circuitry prior to sampling and digitisation, further consideration was made with regards to the sEMG circuitry. sEMG measurements can yield a number of interesting parameters including muscle activation timing, activation shape (e.g. variance) and frequency distribution of the signal. Commercial electromyography systems sample in excess of 1000Hz to allow frequency information up to 500Hz to be faithfully captured (Delsys Inc.). An impact of high frequency sampling is data processing complexity, increased power consumption and high data storage requirements. Primary parameters of interest in this study were muscle activation timing during the stroke and inter-muscle sequencing, not requiring frequency distribution information. Thus a small addition to the hardware circuitry, to perform an extraction of the linear envelope of the muscle data was made. This firmware to hardware trade-off allowed for a significantly lower sample rate (50-60Hz) thus minimising the data that needed to be processed, stored, and most importantly transmitted, by the sensor node.

A wireless Body Sensor Network (BSN) was developed through integrating Zigbee radios into these nodes, with the coordinating node interrogating the slave (measurement) nodes for data at regular intervals (each node was allocated a personal interrogation-upload window upon joining the network), but allowing the slave node radios to be only active for a fraction of the node operation time to upload data and to wake for broadcasts of important cross-network information (e.g start/stop logging data, synchronisation messages). Minimising the number of sensors per node, and sample rate of data minimises the data that needs to be transmitted, and thus the time that the radios need to be in transmit mode, the mode with the highest power consumption. Data analysis was performed off-line in Mathworks® Matlab, but through minimisation of data to minimise processing requirement it is envisaged in future that some feature extraction could take place at the slave node, with further analysis at the coordinator node for real-time feedback to the rower.

Experimentation

System validation and individual oarsman analysis

System validation was performed by simultaneous measurement using the Qualisys motion capture high speed camera system to capture positional and acceleration information from three reflective markers placed upon the nodes sited on the right shank, thigh and central upper back during ergometer rowing. Motion analysis systems employing passive markers and cameras such as Qualisys are regularly used in land-based rowing experimentation [44-46]. Additionally, two Delsys sEMG sensors were synchronised to the Qualisys motion capture system to monitor muscle activity upon the left shank and thigh; as ergometer rowing is symmetrical, the left and right side of the body can be expected to demonstrate similar (though not identical) muscle activity. Electrode placement was made with reference to Gray's Anatomy [47] and the SENIAM-project [48]. The wireless BSN nodes (xyz lowercase axes notation) were aligned to the Qualisys reference system (XYZ uppercase axes notation: X-axis pointing horizontally in the direction of motion along the slide, and the Z-axis vertically upward) when the oarsman is sat upright at rest at backstops (figure 1).

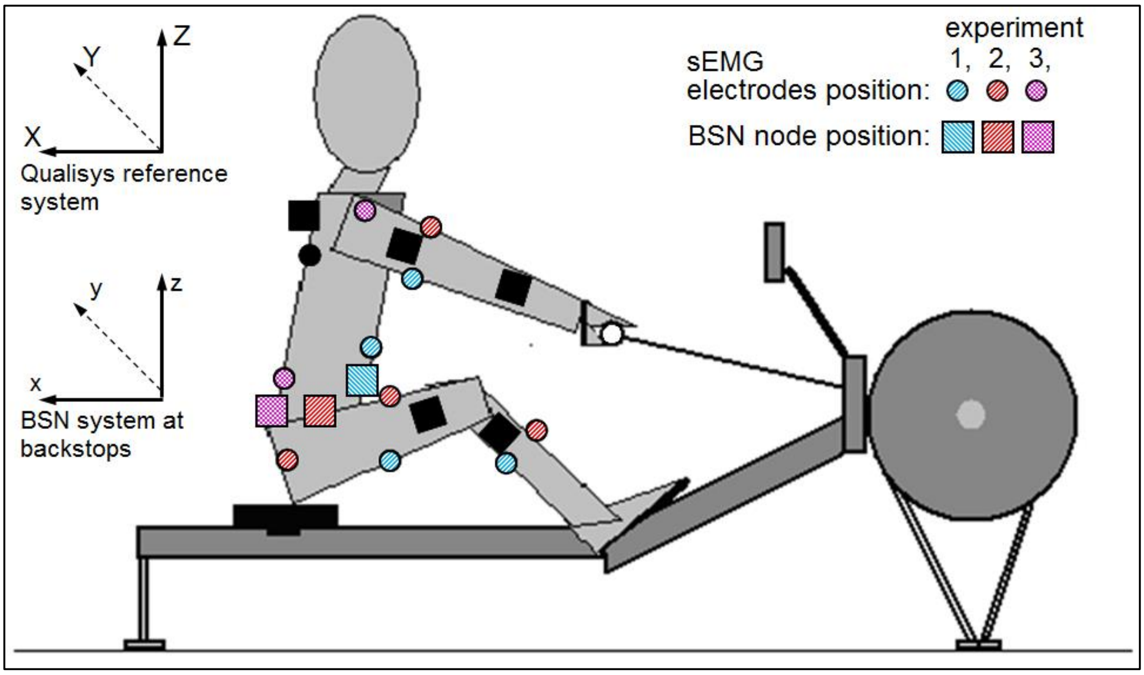

Figure 1. Node placement, and sEMG measurement site.

Node placement over three experiments, with black nodes/electrodes indicating node in common position across the three experiments.

Correlation between the acceleration data captured by the wireless BSN data and the Qualisys system was calculated using Pearson's correlation coefficient [49], first by interpolating the wireless BSN data such that the datasets were of equal size, and then plotting the datasets against each other for visual interpretation prior to calculation of the correlation coefficient (figure 2). As the motion capture system measures only inertial acceleration, the changing gravitational contribution to the acceleration signature measured by the wireless BSN (as it rotates with the oarsman's movement) introduces nonlinearities to the correlation. The stroke cycle was therefore sub-divided into phases of drive, recovery and hands-away/rock-over and showed good correlation: The thigh acceleration in the axis parallel to the ergometer slide (X-axis) was highly correlated with values of r=0.85, 0.88 and 0.87 for drive, recovery and hands-away respectively. The acceleration in the axis perpendicular to the ergometer slide (Z-axis) can achieve a whole stroke correlation of r=0.89. Correlation of the node placed upon the back achieves r=0.82 over the whole stroke for the parallel axis (X-axis), and for the perpendicular (Z-axis) it achieves high correlation of r=0.79 for both drive and hand-away/rock-over, and moderate correlation of r=0.54 for the recovery (this has a slowly changing gravitational component which makes the correlation less easy to interpret). Muscle activity correlation showed high correlation of r=0.85 for the gastrocnemius muscle in the shank, and moderate for the biceps femoris, r=0.54. This concurs with visual inspection of the captured measurements against time; the sEMG signal level upon the thigh node was low, yielding loss of sensitivity of the measurement, indicating possibly less than optimum placement or adhesion of the electrodes; additional differences can be attributed to varying placement/physiology/force application between left and right limbs.

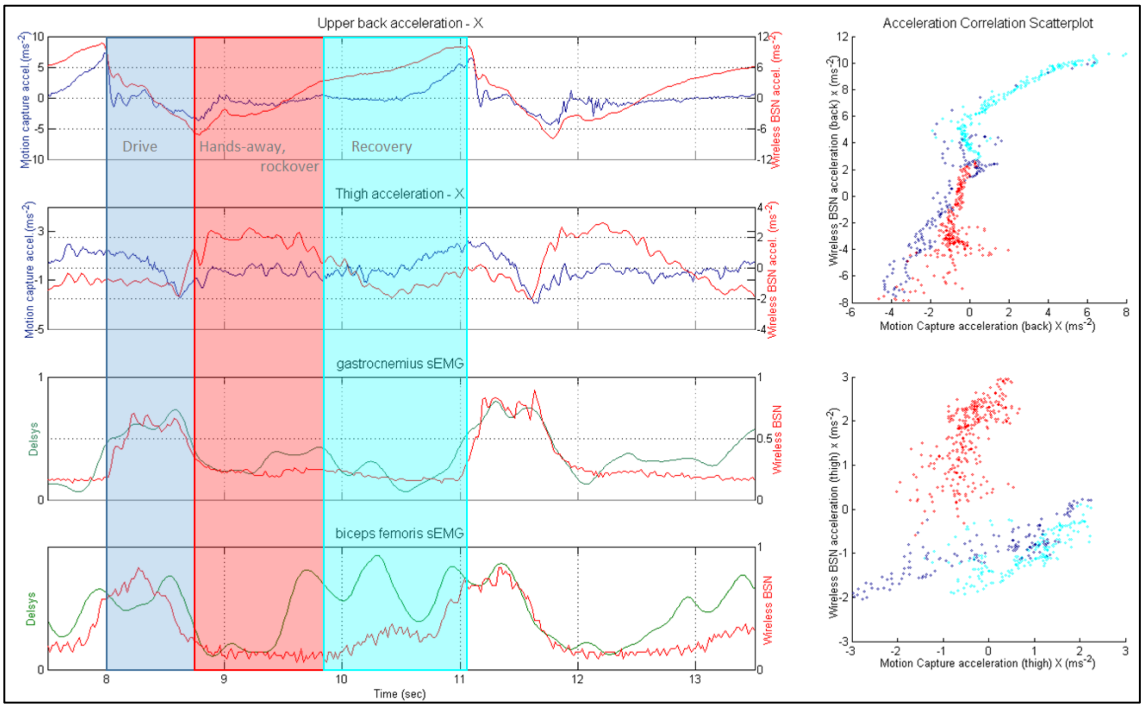

Figure 2. System Validation, comparing upper back and thigh acceleration, and left and right lower limb muscle activity, and examples of correlation scatterplot analysis

With confidence that the system accurately captured information, and that nodes were synchronous across the network, further experimentation was then made on-land and in-boat.

The acceleration signature can be used to align the strokes of multiple experiments (performed at the same stroke rate) where at least one node remains unmoved between experiments. This allows the number of measurements to greatly exceed the number of sensors or wireless nodes available. Figure 1 shows the node positions over 3 ergometer experiments which were aligned using the acceleration signatures of back and thigh nodes which remained in a common position throughout.

The correlation index between the acceleration signatures used in the aligning process was calculated to be r=0.95. Additionally the Variance Ratio (VR) of sensor readings was calculated to determine the oarsman's stroke consistency. The VR optimality criterion was developed by Hershler and Milner [50] to measure repeatability of a signal over a given number of identical footsteps in gait analysis, which they stress is suitable for determination of repeatability of any repetitive signal (VR=0 for completely reproducible signals, and VR=1 for completely irreproducible signals). The oarsman displayed excellent VR values for acceleration signatures and sEMG signals at all nodes, varying from best 0.03 to worst 0.21. Since back and thigh acceleration signatures were used to align the three experiments, it is noted that the VR values of back and thigh acceleration in the axes of interest were 0.06 and 0.1 respectively.

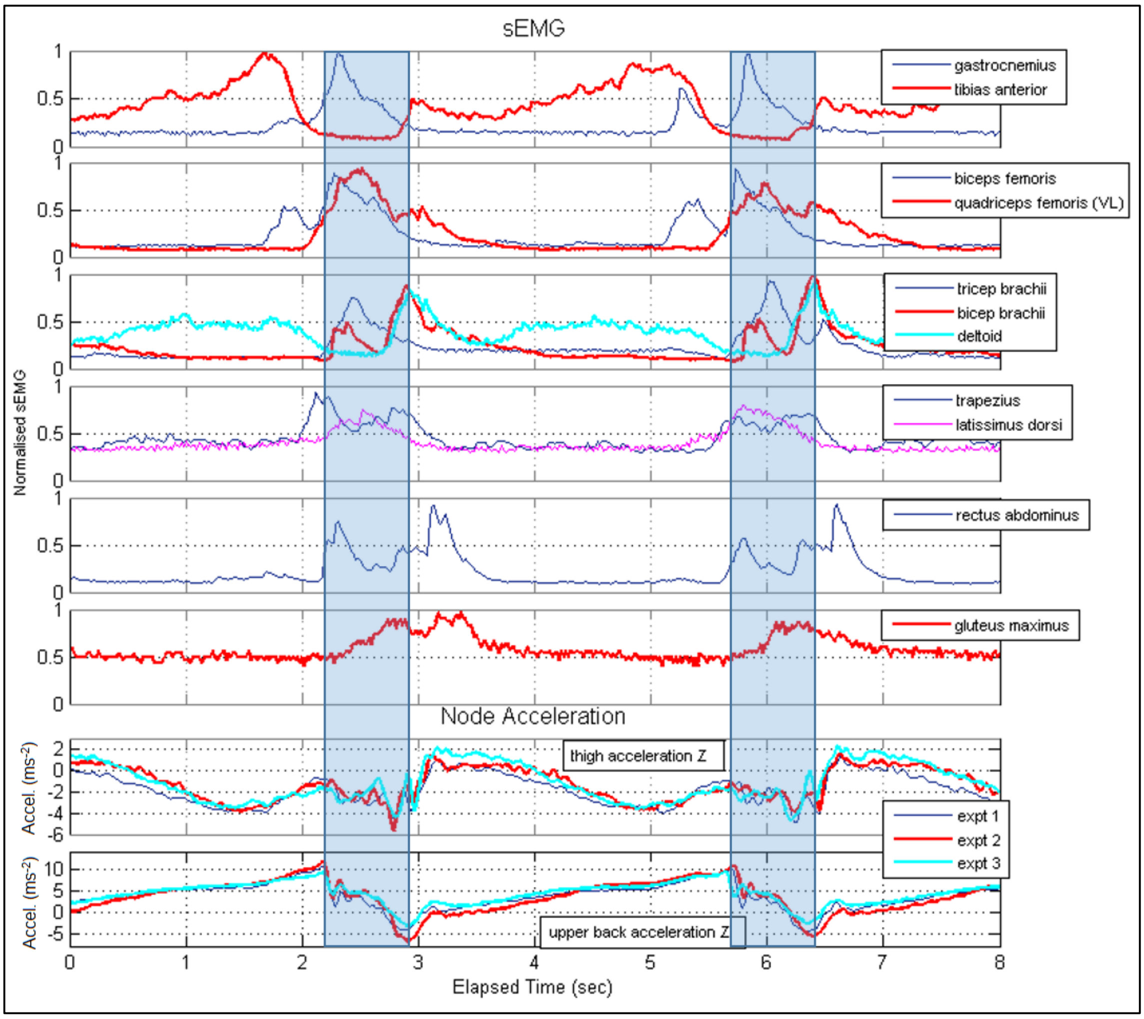

Figure 3. Overlaid muscle activity measurements and acceleration measurements.

The three experiments aligned by thigh and upper back acceleration data to allow analysis of sEMG data from multiple muscles during the rowing stroke; shaded area indicates drive phase.

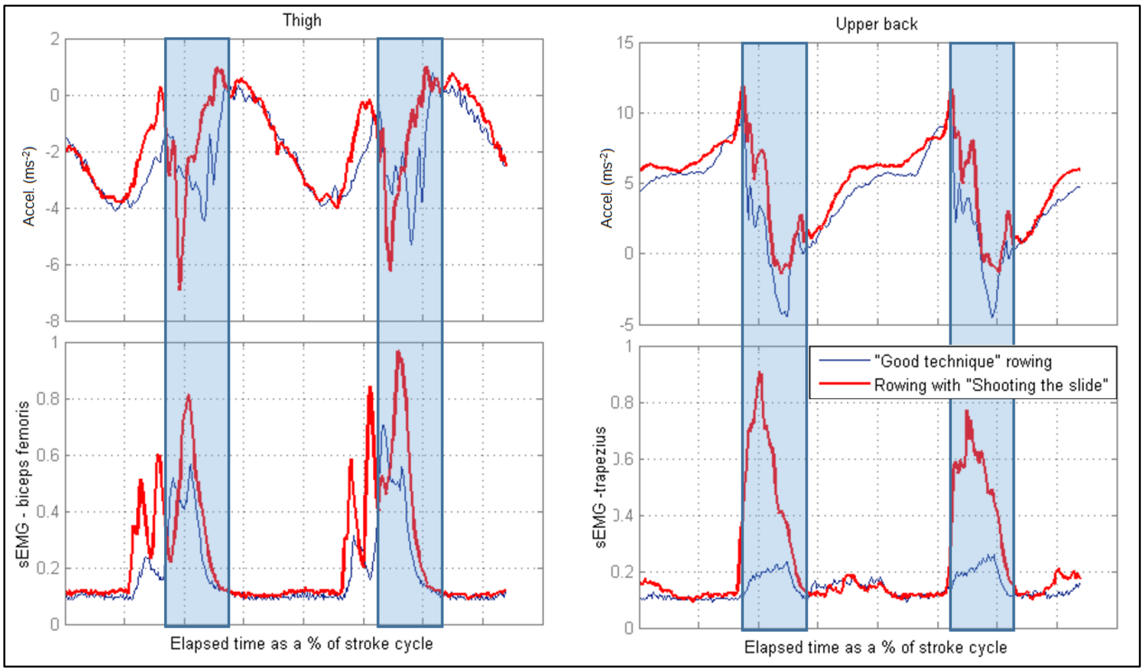

Figure 4. Thigh and Upper back acceleration and sEMG signatures during normal (blue) and "shooting-the-slide" (red) rowing, indicating a marked difference in the drive phase.

The results of combining the three experiments are shown in figure 3, showing the major muscle recruitment over the rowing stroke during the drive and recovery phases, and agrees with muscle recruitment description given by Mazzone [51] of the kinesiology of the rowing stroke. Thus it is interesting to compare measurements using this system of a 'good' rowing stroke with one that displays one of the common rowing 'errors'. One such common error is that of "shooting-the-slide". This error consists of driving with the legs such that the seat leads the back in the drive phase rather than leg and back drive acting as one phase. Figure 3 compares the normal rowing stroke with the oarsman simulating the shooting-the-slide error. Both thigh and back acceleration signatures demonstrate clear differences during the drive phase; the thigh signature indicating that the drive to backstops is achieved over a shorter time at the beginning of the drive phase, and the back signature demonstrates late recruitment into the drive phase. Interestingly, whilst thigh sEMG data also corroborates the short impulsive force in the leg drive, the muscle recruitment of the back during shooting-the-slide indicates greater and earlier activation, possibly due to the back being in extension due to the early drive of the legs. Pearson's correlation coefficient could be used to highlight to the oarsman when his stroke is indicative of shooting the slide, particularly if the drive and recovery phases are compared separately (since it is the drive phase that deviates from 'normal' signature, with the recovery phase remaining largely unaffected). The thigh acceleration data compared in figure 4 demonstrates coefficients of r=0.94 for the recovery, but with correlation for the drive phase dropping from r=0.95 to just r=0.34 when normal and shooting-the-slide are compared. A threshold could thus be set whereby a single numerical score or audible feedback could be produced to feedback in real time to the oarsman. The identification of such non-distracting, real-time feedback has been the focus of a number of studies in sports training and rehabilitation, both in rowing and other sports [52, 53].

Crew analysis

Data collection across distributed wireless nodes was extended to a double sculling boat crew, thus allowing simultaneous monitoring of both oarsmen (at thigh and upper back) in conjunction with the acceleration of the boat. The oarsmen were both club rowers, of similar build, height and rowing experience (Stroke: 38yrs, 187cm, 96Kg, Bow: 34yrs, 187cm, 107Kg). On river measurement took place on a 1km stretch of river, both upstream and downstream, after an initial warm-up row. Oarsmen were instructed to row at 20-22spm, moderate intensity. Figure 5 shows data from the two oarsmen overlaid for comparison. Figure 5(a) demonstrates in-boat measurement, and figure 5(b) demonstrates ergometer measurements made immediately afterwards with no node placement or electrode change in a simulated double scull arrangement with Bow continuing to take timing cues from Stroke. Data transmission failure occurred in the back node of the Stroke oarsman in the on-river measurement but was successful in the subsequent ergometer measurement.

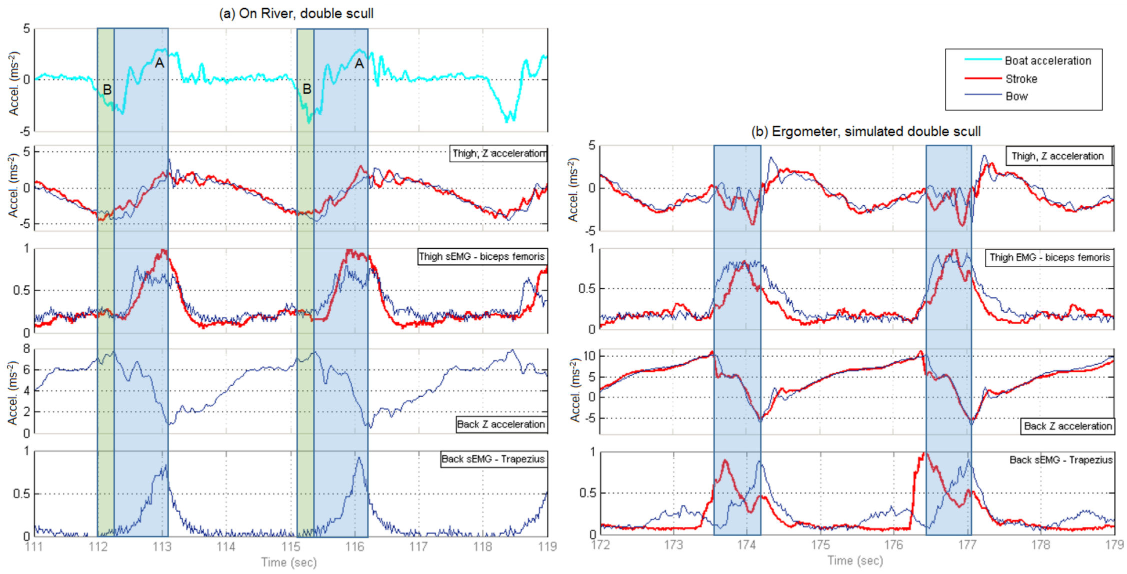

Figure 5. Simultaneous data collection upon two oarsmen in a double-scull, and simulated double-scull upon ergometer.

Back and thigh acceleration, trapezius and biceps femoris sEMG data. Green and blue shaded areas indicate catch and drive respectively.

Correlation coefficients of r=0.91 and r=0.80 are achieved between thigh signatures of the two oarsmen in-boat and on ergometer respectively, and r=0.97 for the ergometer back signature. Analysis can be made between muscle recruitment of the biceps femoris thigh muscles of the two oarsmen, with bow sustaining a steady muscle input over the drive phase and stroke demonstrating a more peaked muscle recruitment over the drive phase. The activation time of the muscle is however very similar. Interestingly, the trapezius muscle recruitment of the two oarsman measured by the back nodes is different, with Stroke's muscle recruitment peaking at the catch and then being sustained throughout the drive, and contrastingly Bow demonstrating a build in muscle activity through the drive phase. This could indicate a difference in technique, different physiology, or a combination of both between the two oarsmen, or highlight the difficulty in matching electrode placement in the large muscle of the back. The acceleration signature of the back node between the two oarsmen indicates that Bow, who follows Stroke, is consistently slightly late at the catch (about 0.05s) but their finishes are matched perfectly. This might corroborate a difference in technique in muscle recruitment in the back.

Discussion and Further work

The experimentation described demonstrates the feasibility and potential of wireless BSN both for analysis of limb and muscle recruitment sequencing in a single oarsman, and to analyse the synchrony between multiple oarsmen in a boat. Acceleration signatures can be used to identify the stroke cycle and used both to analyse variance between strokes, and to allow alignment of data between multiple experiments. Such data can be analysed in conjunction with acceleration data from the boat itself, with a view to maximising the positive acceleration phase of the boat

(‘A’ in figure 5(a)), and minimising the boat deceleration (‘B’), thus maximising the performance of the boat. Optimisation of the system reduces the processing, storage requirements and wireless transmission overhead, thus minimising power consumption and battery longevity, and overall node size and complexity.

With further wireless nodes, such crew experimentation could be extended to monitor more sites across the body, or larger crews. In particular, it would be interesting to analyse multiple muscles in thigh and back to analyse differences in muscle recruitment and technique between oarsmen, and to more closely analyse the muscle recruitment of oarsmen adopting the 4 recognised rowing techniques. Muscle recruitment variation and timing at different rowing intensities and stroke rates could be analysed in conjunction with the boat acceleration to further study the correlation between technique and performance.

Further study is required to determine the best methods to feedback performance to the oarsmen in real time, both of the choice of metric to convey, and in the method of communicating it.

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