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Journal of Electromyography and Kinesiology 15 (2005) 564–575

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

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Rectus femoris surface myoelectric signal cross-talk during static contractions

C.A. Byrne [a,b], G.M. Lyons [a], A.E. Donnelly [b], D.T. O'Keeffe [a,*], H. Hermens [c], A. Nene [c]

[a] *Biomedical Electronics Laboratory, Department of Electronic and Computer Engineering, University of Limerick, National Technological Park, Limerick, Ireland*
[b] *Department of Physical Education and Sport Sciences, University of Limerick, Ireland*
[c] *Het Roessingh Rehabilitation Centre, Enschede, The Netherlands*

Received 3 June 2003; received in revised form 2 February 2005; accepted 25 March 2005

Abstract

The clinical application of EMG requires that the recorded signal is representative of the muscle of interest and is not contaminated with signals from adjacent muscles. Some authors report that surface EMG is not suitable for obtaining information on a single muscle but rather reflects muscle group function [J. Perry, C.S. Easterday, D.J. Antonelli, Surface versus intramuscular electrodes for electromyography of superficial and deep muscles. Physical Therapy 61 (1981) 7–15]. Other authors report however, that surface EMG is adequate to determine individual muscle function, once guidelines pertaining to data acquisition are followed [D.A. Winter, A.J. Fuglevand, S.E. Archer. Cross-talk in surface electromyography: theoretical and practical estimates. Journal of Electromyography and Kinesiology 4 (1994) 15–26]. The aim of this study was to determine whether surface EMG was suitable for monitoring rectus femoris (RF) activity during static contractions. Five healthy subjects, having given written informed consent, participated in this trial. Surface and fine wire EMG from the rectus femoris and the vastus lateralis (VL) muscles were recorded simultaneously during a protocol of static contractions consisting of knee extensions and hip flexions. Ratios were used to quantify the relationship between the surface EMG amplitude value and the fine wire EMG amplitude value for the same contraction. The results showed that hip flexion contractions elicited RF activation only and that knee extension contractions elicited fine wire activity in VL only. When the relationship between RF surface and RF fine wire electrodes was compared for hip flexion and knee extension contractions, it was observed that for all subjects, there was a tendency for increased RF surface activity in the absence of RF fine wire activity during knee extensions. It was concluded that the activity recorded by the RF surface electrode arrangement during knee extension consisted of EMG from the vastii, i.e., cross-talk and that vastus intermedius was the most likely origin of the erroneous signal. Therefore it is concluded that for accurate EMG information from RF, fine wire electrodes are necessary during a range of static contractions.

Keywords: Rectus femoris; EMG; Cross-talk; Fine Wire EMG

1. Introduction

Basmajian and De Luca [1] define EMG cross-talk as, interference of EMG signals from muscles other than the muscle under the recording electrode arrangement. Surface EMG measurements are commonly recorded using a bipolar surface EMG electrode arrangement. However, some authors report that this configuration cannot discriminate between signals originating from the underlying muscle, from adjacent synergist or an opposing antagonist [14]. Skeletal muscle may be viewed as a volume conductor where signals generated from one muscle can be detected from the surface of another

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[*] Corresponding author. Tel.: +353 61 202443; fax: +353 61 338176. *E-mail address:* derek.okeeffe@ul.ie (D.T. O'Keeffe).

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doi:10.1016/j.jelekin.2005.03.002

muscle. Cross-talk recorded as part of a surface signal can confound the interpretation of EMG recordings using a bipolar surface electrode arrangement [8,12,15,26] and hence the ability of this technique to provide accurate information on the contractile state of the muscle being measured is compromised. Double differential amplification or branched electrodes can reduce the effect of cross-talk on surface signal recordings but the problem is not totally resolved, with these techniques [3,15,24].

The issue of cross-talk has been prevalent in surface electromyography discussions and authors have debated the usefulness of surface EMG for experimental and clinical situations since the 1970s [13,16,25]. Fine wire electrodes are one alternative to using surface electrodes for recording EMG. Using a hypodermic needle, wires are inserted into the belly of the muscle being measured, then the hypodermic needle is withdrawn leaving the wire electrodes inside the muscle of interest. Onishi et al. [20] stated that intramuscular fine wire electrodes are suitable to detect the EMG signal of a single muscle selectively during both static and dynamic activities. The relationship between the surface EMG and the signal recorded from intramuscular electrodes is good [2], although in certain instances this relationship changes [23] which may be attributable to cross-talk from adjacent muscles recorded on the surface signal. The fine wire–surface EMG relationship is also dependent on the level of activation of motor units in the region around the fine wire electrode and whether this activation is representative of total muscle activation. A large intramuscular wire electrode area gives a more stable EMG signal and an enhanced surface–fine wire relationship, albeit that the fine wire signal under these circumstances contains a higher frequency component [14].

In general, surface electrodes are preferred in situations where information on total muscle function is required. A surface EMG signal may be considered as a summation of filtered signals due to a number of concurrently active motor units generating volume conducted currents and associated potential fields [5]. Surface EMG electrodes are non-invasive, easy to apply but lack selectivity. Fuglevand et al. [9] provided evidence that electrode size has little influence on signal detection depth, which agrees with the results from other authors [6,17,19]. Fine wire electrodes, on the other hand, take longer to apply, are invasive and can cause pain, cramping and increased tone in persons with spasticity [21].

Authors have reported different methods to test for and isolate cross-talk in surface EMG recordings. One method to identify cross-talk on EMG surface signals involved recording surface and fine wire EMG from the same muscle during a contraction. Surface EMG activity recorded in the absence of fine wire activity indicated cross-talk on the recorded signal. Etnyre and Abraham [7] showed, that during voluntary contractions of the tibialis anterior muscle, a myoelectric signal could be detected with surface electrodes located above the soleus muscle whereas no signals were detected with wire electrodes in the same muscle. An even simpler method to test for cross-talk involves performing a functional resistance test that isolates a specific muscle group and examining the recordings of the non-active muscles [27], although De Luca [4] contends that is can be difficult to ascertain whether adjacent muscles are activated simultaneously during the tests. Solomonow et al. [25] investigated EMG cross-talk in the leg muscles of cats and concluded the EMG cross-talk is not significant where standard EMG protocol is followed. However they also had a caveat in measurement cases where the muscle under analysis is covered by adipose tissue. It can therefore be concluded, that under certain conditions the EMG signal recorded on the skin surface does not originate solely from the muscle over which the electrodes are placed, but may contain signals from muscles in the vicinity of the recording electrodes.

The purpose of this study was twofold: firstly to determine whether the surface EMG signal recorded from the rectus femoris (RF) is a true representation of the activation pattern of that muscle or whether it is contaminated with cross-talk from the vastii; secondly, to determine the relationship that exists between fine wire and surface EMG signals of rectus femoris during different static contraction protocols. The RF muscle was selected because EMG measurements of this muscle are routinely used to select surgical procedures in children with CP to improve knee function during gait [10,21].

2. Methodology

2.1. Subjects

Five healthy male volunteers were recruited from a local student population, ages ranging from 23 to 33 years old (26 ± 4). Each subject underwent a medical examination and completed an exclusion/inclusion criteria form, before participating in the trial. Healthy adult subjects without previous orthopaedic or neurologic pathologies participated in the trial. Written informed consent was obtained when subjects had read the volunteer information sheet and questions pertaining to the study had been answered to their satisfaction. For the duration of the experiment all subjects wore shorts and a T-shirt and all measurements were performed in bare feet. This study received ethical approval from the medical ethics committee of the Het Roessingh hospital and the study was conducted in the gait laboratory of Roessingh Research and Development, Enschede, Holland.

2.2. Fine wire electrodes

The fine wire electrodes (The California Fine Company, 338 South 4th Street, Grover City, CA 93433, USA) were stainless steel, nylon insulated with a diameter of 50 μm. The wire electrodes were prepared using the method described by Basmajian and De Luca [1]. A 2 mm section of insulation was removed at the wire tip using heat, exposing a recording surface, and the inter-tip distance was set at 2 mm. The recording surface area of the fine wire and inter-tip distance were confirmed using magnification.

2.2.1. Fine wire electrode placement

Subjects sat on a plinth (relatively firm surface), whilst electrode locations were selected and electrodes were applied, for EMG measurements. For each electrode location, the surrounding area was shaved with a disposable razor and then cleaned by rubbing the area with cotton wool soaked in alcohol. The alcohol was allowed to dry before placement/insertion of the electrodes. For RF, a line was measured between the anterior superior illiac spine and the superior border of the patella, and the fine wire electrode was inserted at 50% of the distance between both anatomical landmarks. The fine wire electrode was inserted into the muscle by a medical physician using a medical disposable needle and was withdrawn once the correct location had been selected. After extraction of the hypodermic needle, a loop was formed in the wires at the skin entrance to prevent electrode migration due to muscle contraction. The wires were then taped to the skin to avoid accidental dislodgement and then inserted into coiled springs where the signal is amplified prior to recording. The coiled springs were taped to the leg to minimise movement and a series of contractions was performed to fix the fine wire electrodes in place. Each subject was asked to flex the hip while in a seated position to confirm accurate placement of the fine wire electrodes in the RF and visual inspection of the recorded signal confirmed accurate or inaccurate electrode placement, using the technique of Ounpuu et al. [21].For vastus lateralis (VL), a line was measured between the anterior superior iliac spine and the lateral border of the patella. The fine wire electrode was inserted at two thirds of the distance distal of the anterior superior iliac spine. To ensure accurate placement of the electrodes, fine wire EMG was recorded while the subject extended the knee.

Fine wire electrodes must be accurately inserted and firmly lodged, to obtain a high quality EMG recording. Perry et al. [22] stated that in testing for comfort and placement, several strong contractions would firmly fix the wires in place. Similarly, Basmajian and De Luca [1] recommended that a minimum of six contractions be performed before any EMG measurements were recorded to ensure firm fixation of the fine wire electrodes. All subject performed a series of maximal contractions and the limb was moved through the full range of motion before EMG recordings were taken.

2.3. Surface electrodes

Square shaped silver–silver chloride (Ag/AgCl) electrodes (Meditrace Pellet 180, The Netherlands) with a 10 mm × 10 mm recording area, and a 22 mm centre to centre inter-electrode distance were used for surface EMG recordings. For both the RF and the VL, the surface electrodes were positioned on either side of the fine wire electrodes parallel to the direction of the muscle fibres for that muscle [11]. Manual muscle tests, identical to those performed after fine wire electrode insertion, were performed to confirm accurate placement of the surface electrodes and EMG recordings were observed visually to confirm accurate surface electrode placement.

2.4. Contraction protocol

(a) *Vastii protocol.* All subjects began in a seated position on a plinth with a knee and hip angle of ninety degrees with the back straight. Two resting EMG measurements were recorded at this point as an initial reference, with the subject in a relaxed state. Each subject then extended the knee to angles of 30°, 60° and 90° from the starting point while EMG was recorded simultaneously from both muscles at each knee angle position. Subsequently 1.13 and 2.26 kg weights were attached at the ankle and the contraction protocol was repeated using the same angles. In all cases EMG was recorded for a 5–10 s period for each contraction and the mean linear envelope value over 3 s was used in the results analysis section. Two EMG measurements were taken for each angle/weight combination and all muscle contractions were isometric.

(b) *Rectus femoris protocol.* For Rectus Femoris, two baseline measurements were first recorded with the subject in the resting position. Subjects then flexed the hip to two angles, a low angle of approximately 15° and a high angle of approximately 30° and EMG was recorded from both muscles in each case. Subjects were instructed to keep their back straight and to hang their knee so that their leg was perpendicular with the ground. For both knee angles a 1.13-kg weight followed by a 2.26 kg weight were placed around the ankle and two EMG recordings were taken for each angle/weight combination.

The order in which all muscle contractions were performed was randomized to prevent fatigue or bias in the results. Each contraction protocol was designed to elicit an EMG response from different muscles. Knee extension contractions were designed to activate the vastii only while the hip flexion contractions have been shown to activate rectus femoris only [21]. For knee extension contractions, rectus femoris surface EMG activity recorded in the absence of corresponding fine wire EMG activity, could indicate possible cross-talk from the vastii muscles.

2.5. Data acquisition

Data collection was performed using a K-lab EMG measurement system (Biometrics Europe, Printerweg 11, 3821 AP Amersfoort, The Netherlands). All four data channels were recorded simultaneously, two surface EMG channels and two fine wire EMG channels. The sampling frequency for all channels was 2 kHz which was in line with the Nyquist Theorem and prevented anti-aliasing of the EMG signals. Differential amplification and a hardware high pass filter (third order Butterworth) with a cut off frequency of 20 Hz were implemented on all EMG channels to increase the signal-to-noise ratio. The measurement system had an input impedance of 100 MΩ and a common mode rejection ratio of 100 dB. A gain of 500 was used to increase signal amplitude and a 12-bit A/D converter produced an output in digital format. Data was stored using the VICON™ software in C3D format and converted to ASCII format for post-processing in MATLAB™ (The Mathworks Inc., MA, USA).

2.6. Data analysis

Using MATLAB™ surface and fine wire EMG data channels were first band pass filtered, surface EMG signals were filtered between 20 and 500 Hz and fine wire EMG signals between 100 and 500 Hz. Power spectrum analysis of the fine wire EMG signal showed that most of the signal power lay between 150 and 250 Hz. All EMG data was then full wave rectified and low pass filtered using a second order Butterworth filter with a cut off frequency of 25 Hz to obtain a linear envelope. A 3-s mean of the linear envelope during the 5–10 s contraction was calculated for each contraction type and the results were transferred to EXCEL (Microsoft, Washington, USA) for further analysis.

3. Results

3.1. Vastus lateralis – knee extension contractions

As stated previously, knee extension contractions were designed to elicit VL EMG activity only. Fig. 1 shows data that are typical for all subjects. EMG was recorded at rest (knee angle 90 degrees) to check that the signal was not contaminated with noise from external sources. Two knee extension contractions are represented for each of the three angles used, namely 30°, 60° and 90° of extension from the resting state. Fig. 1 shows that VL EMG activity in the absence of RF EMG activity. In general, it was noted that as the knee extension angle was increased, there was a corresponding increase in the recorded EMG amplitude of both VL surface and fine wire channels (Fig. 1). As the knee extended, there was a corresponding increase in surface and fine wire EMG amplitude that resulted from an increased moment acting on the knee joint due to gravity. No RF fine wire EMG activity was detected, however, a slight increase in RF surface EMG activity was observed which corresponded to VL amplitude increases.

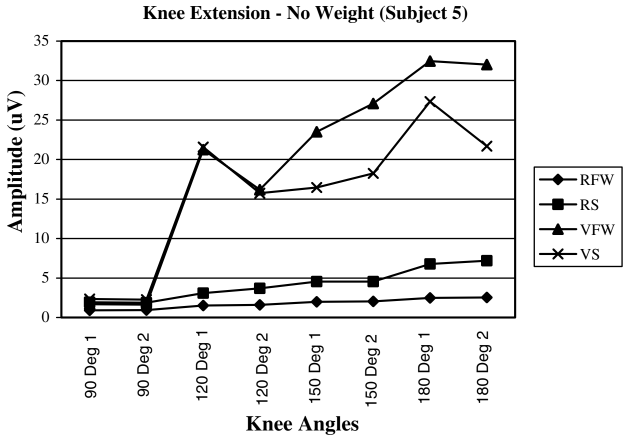

Fig. 1. EMG values recorded during knee extension contractions for RF and VL using both surface and fine wire electrodes (RFW, rectus femoris fine wire; RS, rectus femoris surface; VFW, vastus lateralis fine wire; VS, vastus lateralis surface). X-axis nomenclature 1 and 2 refers to initial and repeated measure.

Fig. 2 shows that a relationship exists between vastus lateralis fine wire data (VFW) and vastus lateralis surface data (VS) for knee extension contractions. A Pearson's Correlation Coefficient was calculated to describe this relationship. The correlation coefficient measures the strength and direction of the linear association between two quantitative variables, in this instance VL surface and VL fine wire EMG amplitudes [18]. The Pearson's correlation coefficient was 0.731 ($p < 0.01$) – a strong correlation. When a regression model was formed for VS using VFW, the coefficient of determination was 53.5% indicating that during knee extension contractions 53.5% of the variation in VS is explained by VFW. When an ANOVA is performed on VS with VFW as a covariate then the inclusion of subject and subject/weight level interaction brought the amount of variation in VS explained up to 96.6% ($R^2 = 0.966$).

For the same muscle contraction, EMG recordings using surface and fine wire electrodes have different

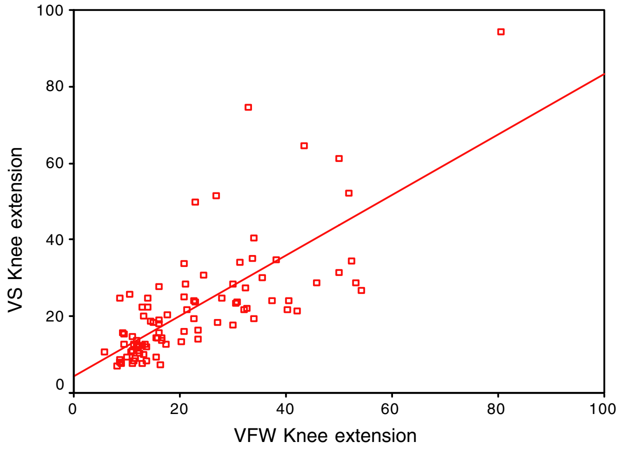

Fig. 2. Graph of VFW–VS relationship for knee extension contractions for all subjects (axes units in μV).

amplitudes. To quantify this relationship, a within subject ratio was calculated between surface and fine wire electrodes for all contractions. The ratios were used to give a figure that was representative of the average relationship between surface and fine wire signal amplitudes for VL during this contraction type for each subject. For all contractions the mean EMG value of the fine wire signal was divided by the mean EMG value recorded for the surface signal. A mean ratio was then calculated that represented the size of one signal compared to the other. Ratio results for VL during knee extension contractions are given in Table 1.

A Pearson's correlation coefficient was calculated to determine the within subject relationship between EMG fine wire and surface channels over a range of weights and knee angles (Table 1). All subjects exhibited correlation coefficients values greater than 0.88. The group mean correlation coefficient was 0.93.

In some experiments EMG amplitude normalisation is used to compare data between subjects. However for this study, amplitude normalisation was not used to compare surface and fine wire EMG data due to the varying surface/fine wire relationship across the range of intensities. The ratio system used allows for an accurate within subject comparison and was used instead of amplitude normalization.

3.2. Rectus femoris – hip flexion contractions

For all subjects, hip flexion resulted in RF activation only. Typical subject data is shown in Fig. 3. Hip flexion contractions served a twofold purpose (1) to confirm that hip flexion elicits RF activation only and (2) to determine the relationship between RF surface and fine wire channels for a range of ankle weights and joint angles. From Fig. 3, it may be seen that with increasing RF fine wire EMG intensity, there was an increase in RF surface EMG activity. For all subjects the high hip flexion angle did not always result in EMG activation levels greater than those recorded at the low hip flexion angles.

Fig. 4 shows that a relationship exists between rectus femoris fine wire data (RFW) and rectus femoris surface data (RS) for hip flexion contractions. A Pearson's correlation coefficient was calculated to examine this relationship. The Pearson's correlation coefficient was 0.579 ($p < 0.01$) – a modest correlation. When a regression model was formed for RS using RFW, the coefficient of determination was 33.6% indicating that during hip flexion contractions 33.6% of the variation in RS is explained by RFW. Therefore the relationship between RFW and RS was weaker for hip flexion when compared to the same relationship for knee extension contractions. The ANOVA for RS using RFW as a

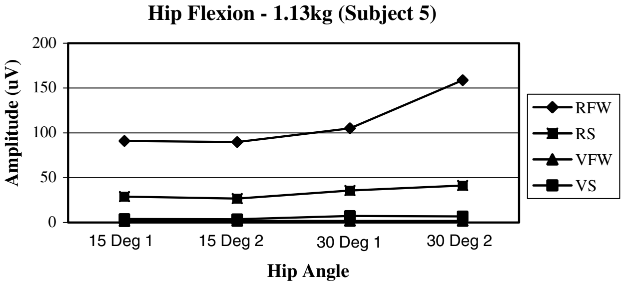

Fig. 3. Mean EMG amplitude values recorded during hip flexion contractions from sitting position for RF and VL, using both surface and fine wire electrodes (lowhf1, low hip flexion contraction 1; highhf1, high hip flexion contraction1; RFW, rectus femoris fine wire; RS, rectus femoris surface; VFW, vastus lateralis fine wire; VS, vastus lateralis surface). *X*-axis nomenclature 1 and 2 refers to initial and repeated measure.

Table 1
Ratio (mean and standard deviation) to compare the absolute EMG amplitude value of VL surface and VL fine wire channels during knee extension contractions

Weight/Angle	VFW/VS				
	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Mean ratio	1.46	1.42	0.62	0.88	1.14
Standard deviation	0.38	0.26	0.17	0.17	0.20
Pearson's correlation coefficient	0.97	0.96	0.89	0.94	0.9

For all contractions the mean EMG value for the fine wire channel was divided by the mean EMG value of the surface channel. A Pearson's correlation coefficient is also given for the within subject relationship between VFW and VS data (VFW, vastus lateralis fine wire; VS, vastus lateralis surface; K.E., knee extension).

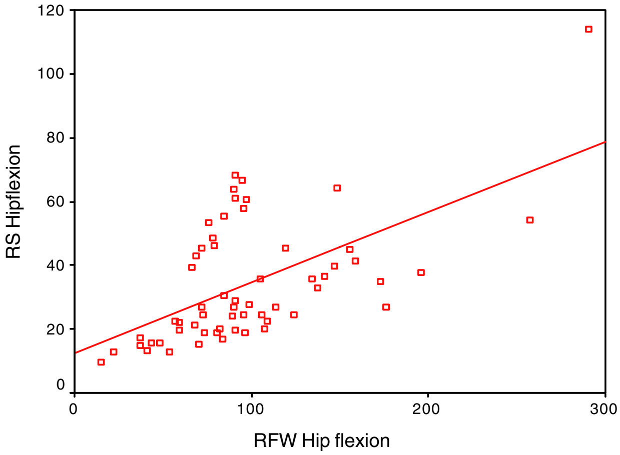

Fig. 4. Graph of RFW–RS relationship for hip flexion contractions for all subjects (axes units in μV).

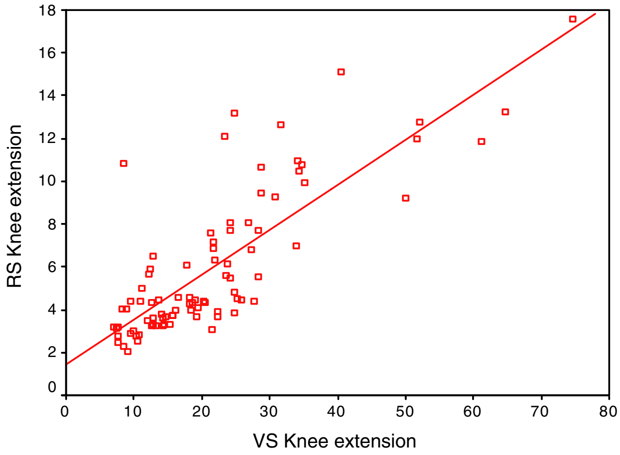

Fig. 5. VS–RS relationship during knee extension contractions for all subjects. When the VS–RS relationship was examined a Pearson's Correlation coefficient of 0.809 ($p < 0.001$) was observed – this represents a strong correlation (axes units in μV).

covariate with the inclusion of subject, weight and subject/weight level interaction brought the amount of variation in RS explained up to 95.9% ($R^2 = 0.959$).

Ratios were calculated to determine the average relationship between RF surface and fine wire EMG channels during hip flexion and the results for each subject are shown in Table 2.

A Pearson's correlation coefficient was calculated to determine the within subject relationship between EMG fine wire and surface channels over a range of weights and knee angles (Table 2). All subjects exhibited Pearson's correlation coefficients values that were greater than 0.65. The group mean correlation coefficient was 0.77.

3.3. Rectus femoris – knee extension contractions

When RS was plotted against VS for knee extension contractions, it was observed that in general an amplitude increase in one channel corresponded to an amplitude increase in the other channel (Fig. 5).

When a regression was performed predicting RS (knee extension contractions) from RFW and VFW it was found that RFW was included in the model before VFW and this accounted for 62.5% of the variation in RS by itself. When VFW was also included then both RFW and VFW now accounted for 82.6% of the variation in RS. When an ANOVA was carried out on RS over subjects and weight and angle level then both RFW and VFW were significant ($p < 0.01$) as well as subject and subject/weight interactions which allowed for variation between subjects and the differing variation over the different levels for each subject. The different levels for weights and angles were not significant on their own.

Ratios were calculated to determine the average relationship between RF surface and fine wire EMG channels during the knee extension contractions and the results for each subject are shown in Table 3. The ratios here can be compared with hip flexion contraction ratios for the same EMG channels.

A Pearson's correlation coefficient was calculated to determine the within subject relationship between EMG fine wire and surface channels over a range of weights and knee angles (Table 3). All subjects exhibited correlation coefficients values greater than 0.62. The group mean correlation coefficient was 0.8.

The ratio for RFW/RS was plotted against the different weights and angles for both knee extension (Table 4)

Table 2
Ratio (mean and standard deviation) to compare the absolute EMG amplitude value of RF surface and RF fine wire channels during hip flexion contractions

Weight/Angle	RFW/RS				
	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Mean ratio	2.96	2.67	4.19	1.73	4.40
Standard deviation	1.02	0.66	0.79	0.49	1.04
Pearson's correlation coefficient	0.79	0.94	0.66	0.7	0.77

For all contractions the mean EMG value for the fine wire channel was divided by the mean EMG value of the surface channel. A Pearson's correlation coefficient is also given for the within subject relationship between RFW and RS data (RFW, rectus femoris fine wire; RS, rectus femoris surface; HF, hip flexion).

Table 3
Ratio to compare the absolute EMG amplitude value of RF surface and RF fine wire channels during knee extension contractions

Weight/Angle	RFW/RS				
	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Mean ratio	0.38	0.35	0.56	0.37	0.47
Standard deviation	0.13	0.14	0.12	0.10	0.22
Pearson's correlation coefficient	0.77	0.63	0.90	0.83	0.86

For all contractions the mean EMG value for the fine wire channel was divided by the mean EMG value of the surface channel. A Pearson's correlation coefficient is also given for the within subject relationship between RFW and RS data (RFW, rectus femoris fine wire; RS, rectus femoris surface; K.E., knee extension).

Table 4
Data table for RFW/RS ratio plots (knee extension)

	Descriptives			
	Mean	SD	Min.	Max.
RFW/RFS for knee extension				
No weight 30	0.488	0.081	0.39	0.641
No weight 60	0.435	0.136	0.262	0.7
No weight 90	0.408	0.28	0.17	0.777
1.13 kg 30	0.453	0.075	0.362	0.607
1.13 kg 60	0.417	0.106	0.296	0.636
1.13 kg 90	0.315	0.083	0.201	0.432
2.26 kg 30	0.44	0.149	0.273	0.75
2.26 kg 60	0.386	0.183	0.22	0.824
2.26 kg 90	0.374	0.181	0.172	0.696
Total	0.414	0.142	0.17	0.824

and hip flexion contractions (Table 5) and there did not appear to be any particular relationship changes over the different levels for each contraction type. The ANOVA results confirmed these findings, $p = 0.316$ for knee extension and $p = 0.743$ for hip flexion contractions. Graphs of the mean ratios for each weight/angle combination are also shown (Figs. 6 and 7).

Fig. 8 shows how the ratio relationship changes for RF fine wire EMG and surface EMG recordings for the two different contraction types. The group mean ratio for the RF fine wire:RF surface relationship was 3.2 ± 1.1 for hip flexion contractions and 0.42 ± 0.09 for knee extension contractions.

The Pearson's correlation coefficient between RS and RFW was 0.793 and 0.579 for knee extension and hip flexion contractions, respectively. These can be tested against the null hypothesis that they are equal and that the relationship between RS and RFW is the same for both knee extension and hip flexion. When a test based on the Fisher Z transformation was performed, the significance level was <0.05, which means that it is very un-

Table 5
Data table for RFW/RS ratio plots (hip flexion)

	Descriptives			
	Mean	SD	Min.	Max.
RFW/RS for hip flexion				
No weight low HF	3.5	1.16	1.51	5.12
No weight high HF	3.62	1.71	1.57	6.52
1.13 kg low HF	3.1	1.07	1.33	4.52
1.13 kg high HF	2.82	1.01	1.48	4.67
2.26 kg low HF	2.96	1.33	1.4	4.89
2.26 kg high HF	3.12	1.43	1.41	4.94
Total	3.19	1.29	1.33	6.52

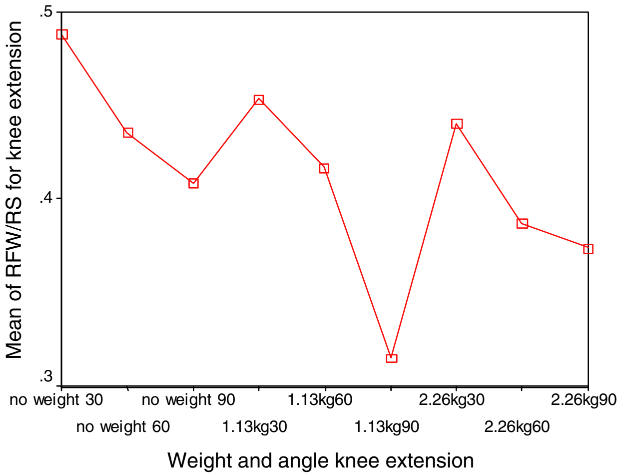

Fig. 6. Plot of RFW/RS ratio means (group) for each weight angle combination during knee extension contractions.

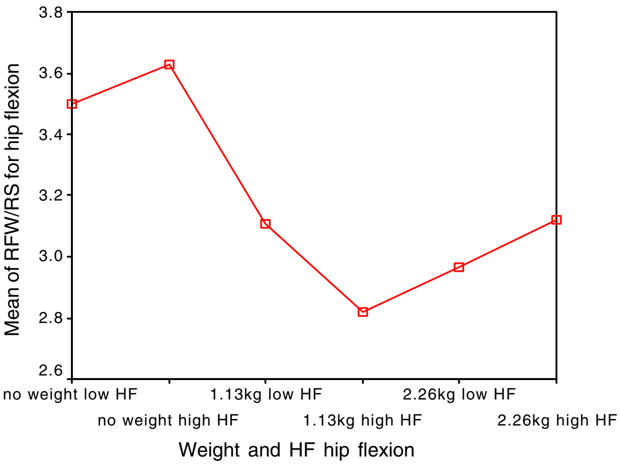

Fig. 7. Plot of RFW/RS ratio means (group) for each weight/angle combination during hip flexion contractions.

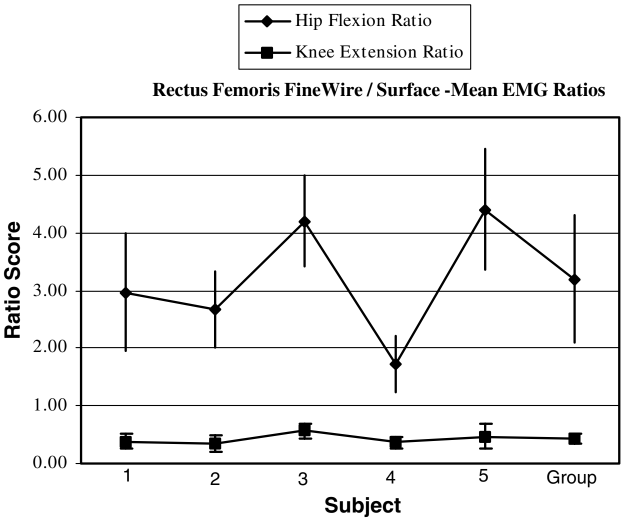

Fig. 8. Mean within subject ratios for knee extension and hip flexion contractions.

likely that the relationship between RS and RFW is the same for both knee extension and hip flexion. If this test was used as the main test of whether the relationships were different then the power level of this test for the number of sample points used is at least 70%.

4. Discussion

The principal argument against the use of surface electrodes to determine muscle activation patterns, is the perceived problem of cross-talk or activity from adjacent muscles, that produces a signal on the electrode of the muscle of interest [21]. One of the main aims of this study was to determine the effectiveness of surface electrodes for recording EMG from RF during static contractions. In this experiment the relationship between surface and intramuscular EMG was determined for RF and VL using muscle contractions that isolated each muscle. Ounpuu et al. [21] showed that a test of voluntary hip flexion in a seated position recruited RF as a hip flexor without any simultaneous VL activity.

In this study it was observed that knee extension elicited VL activation only, when the knee joint was prevented from hyper-extending. Similarly hip flexion was shown to elicit RF activation only – both these measurements considered fine wire signals only as these are true representations of whether the muscle is active or not. When a combination contraction is performed it is possible to see the effect of the two contraction types on muscle activation patterns. For the combination contraction the leg begins in the resting position, after which the subjects extended the leg to 180° knee extension. The knee extension only part of the contraction is shown to elicit VFW and surface activity (Fig. 9) with no RFW activity (Fig. 10). The knee extension phase is followed by a phase of combined knee extension and hip flexion. This part of the contraction is designed to activate the RF muscle (Fig. 10). VL will stay active throughout this phase to preserve knee extension. For the example shown below the first 2.5 s correspond to the resting state. The knee extension phase lasts from 2.5 to 4.7 s and the final phase of combined

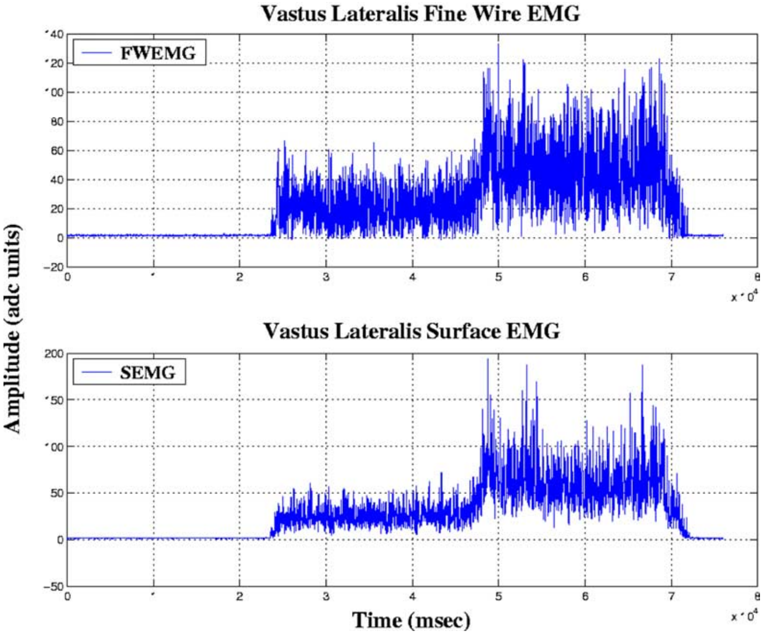

Fig. 9. Sample vastus lateralis activation pattern (surface and fine wire) during the combination contraction (adc, analog digital conversion units).

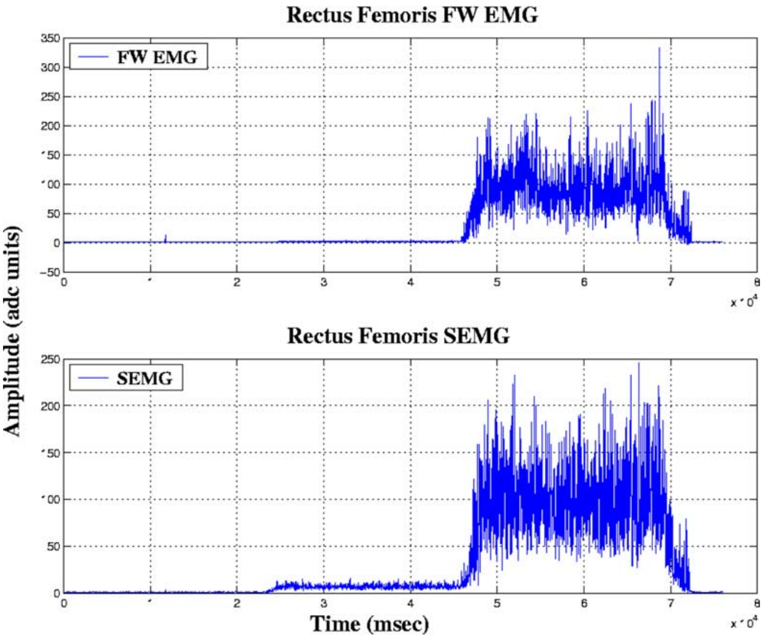

Fig. 10. Sample rectus femoris activation (surface and fine wire) during the combination contraction (adc, analog digital conversion units).

knee extension and hip flexion lasts from approximately 4.7 to 7 s.

It should be noted that from Fig. 10 it can be observed that there is slight RF surface activation in the absence of fine wire activity. It should also be noted that for the results analysis, EMG was recorded from all four channels for each contraction and a 3-s mean value of the processed signal was used.

A correlation coefficient measures the strength and direction of the linear association between two quantitative variables [18]. In this experiment Pearson's correlation coefficients were used to measure the relationship between surface and fine wire EMG channels for VL and RF during knee extension and hip flexion contractions. When all subject's data were considered a Pearson's correlation coefficient for the VFW/VS surface relationship was 0.731 ($p < 0.01$) for knee extension contractions – a strong correlation. A correlation coefficient of 0.579 ($p < 0.01$) was calculated for the RFW/RS relationship during hip flexion contractions – a modest correlation. For both types of contraction high correlation values are expected since an increase in fine wire EMG amplitude should lead to a corresponding increase in surface EMG amplitude. Within subject correlation coefficients for the same relationships are as expected somewhat higher than overall correlation coefficient values. Within subject correlation coefficients for the VFW/VS relationship during knee extension contractions ranged from 0.89 to 0.97 with a group mean correlation coefficient of 0.93. Similarly within subject correlation coefficients for the RFW/RS relationship during hip flexion contractions ranged from 0.66 to 0.94 with a group mean correlation coefficient of 0.77. It is difficult to explain the variance in correlation coefficients observed both between contractions and between subjects. The variation observed between contraction types may be due to a more homogenous distribution of motor units within VL compared to RF. Correlations can be enhanced by increasing the N number used to calculate the correlation coefficient. In this instance the number of contractions used to calculate the VFW/VS correlation coefficient was greater than that used to calculate the RFW/RS coefficients, $n = 18$ versus $n = 12$.

A regression model formed for VS using VFW showed that for knee extension contractions VFW explained 53.5% of the variation in VS. An ANOVA showed that when subject and the interaction between subject and the weight used are included the amount of variation that was explained in VS increases to 96.6%. The same type of analysis was performed for the RFW/RS relationship during hip flexion contractions. A regression model formed for RS using RFW indicated that during hip flexion contractions 33.6% of the variation in RS is explained by RFW. The ANOVA for RS using RFW as a covariate with the inclusion of subject, weight and subject/weight level interaction brought the amount of variation in RS explained up to 95.9% ($R^2 = 0.959$). For both channels a close relationship existed between the surface and fine wire EMG channel when all variables were considered.

The relationship between RS and VS during knee extension contractions was also considered to see what relationship existed between the two EMG channels. As noted above (Fig. 9) cross-talk may be recorded on the RS signal. In theory if there were no cross-talk and no muscle co-contraction there should be no relationship between the two channels. When a regression was performed predicting RS (knee extension contractions) from RFW and VFW it was found that RFW was included in the model before VFW and this accounted for 62.5% of the variation in RS by itself. When VFW was also included then both RFW and VFW now accounted for 82.6% of the variation in RS. Interestingly when a regression was carried out for RS (knee extension), including VS, RFW and VFW in the model then, VS was the most predictive variable of RS. VS explained 65.4% of the variation in RS and when combined with RFW these two explained 73.4% of the variation in RS. When VFW was added to the model the three variables VS, RFW and VFW explained 83.6% of the variation in RS but in this final model the term for VS became non-significant once the term for VFW was added indicating that the VFW had explained most of the variation originally explained by VS. This suggested that both RFW and VFW are needed to explain variation in RS and that both VFW and RFW contribute to variations in RS. It also suggests that RFW is a better predictor of RS than VFW.

Ratios were calculated to explain the average within subject relationship between RFW/RS and VFW/VS for hip flexion and knee extension contractions. The RFW/RS relationship was of particular interest since it was hypothesised that there was a change in the relationship between contractions which was due to cross-talk recorded on the RS channel. For the ratio system the fine wire electrode value was divided by the corresponding surface electrode value for each individual contraction. A within subject, within contraction mean was calculated to give a value that represented the average relationship between the surface and fine wire channels for the same muscle.

As stated previously the fine wire EMG–surface EMG relationship is non-linear and varies across different contractions. Onishi et al. [20] stated that during contractions of different intensity, the effect of motor units surrounding a fine wire electrode has an unbalanced influence on the surface EMG–fine wire EMG relationship. If large motor units surround the electrode, small motor units at a distance to the recording electrode are found to be smaller at lower force levels and as force increases larger motor units near to the recording electrode show larger amplitude levels. The relationship can also be affected by muscle length during EMG signal recording. A shortened muscle length will result in a higher concentration of muscle fibres beneath the recording electrode which can lead to an amplified surface EMG signal resulting in a reduced fine wire EMG:surface EMG relationship.

For VL during knee extension contractions the individual subject ratio ranged from 0.62 to 1.46, a ratio greater than one indicating a larger fine wire EMG amplitude compared to the surface EMG amplitude for the same contraction. A ratio less than one indicated a larger surface EMG amplitude relative to the fine wire EMG amplitude. For RF during hip flexion contractions the individual subject ratio ranged from 1.84 to 4.4 with a group mean value of 3.2. This indicated that for RF contractions the fine wire EMG amplitude value was greater than the surface EMG value for all subjects during hip flexion contractions. For knee extension contractions RF ratios range from 0.35 to 0.56 with a group mean value of 0.42. These scores indicate a change in the relationship between the surface EMG and fine wire EMG signals for the two types of muscle contraction, a larger surface EMG signal was recorded relative to the fine wire EMG signal for knee extension contractions. Using the ratios obtained from the hip flexion contractions, it can be assumed that the increase in the surface EMG signal observed on the RF channel relative to the fine wire EMG signal for the same muscle is due to EMG being recorded from a muscle other than the RF. It may be possible that other RF motor units not picked up by the FW EMG can also contribute but it is not thought that their contribution is significant. Such activity would be recorded on the RF surface signal but would not be recorded on the fine wire signal due to differences in recording area for both electrodes. In this experiment fine wire activity was recorded from VL but was assumed to be representative of vastus lateralis and vastus intermedius activity. Therefore it is postulated that activity from vastus intermedius during knee extension is recorded on the RF surface EMG signal.

When the ratio for RFW/RS was plotted against the different weights and angles for both knee extension and hip flexion contractions there did not appear to be any particular relationship changes over the different levels for each contraction type. This was confirmed using an ANOVA. Therefore there is no within contraction change in the RFW/RS relationship. The Pearson's correlation coefficients between RS and RFW were 0.793 and 0.579 for knee extension and hip flexion contractions, respectively. These can be tested against the null hypothesis that they are equal and that the relationship between RS and RFW is the same for both knee extension and hip flexion. When a test based on the Fisher Z transformation was performed, the significance level was <0.05, which means that it is very unlikely that the relationship between RS and RFW is the same for both knee extension and hip flexion. If this test was used as the main test of whether the relationships were different then the power level of this test for the number of sample points used is at least 70%.

Based on the evidence presented it can be concluded that a relationship exists between RFW and RS during hip flexion contractions and that this relationship changes for knee extension contractions. It would appear that the change in the RFW/RS relationship is due to cross-talk recorded on the surface EMG signal, RS. Ounpuu et al. [21] has shown that fine wire electrodes were not necessary for the collection of data from the vastus medialis (VM) and VL if the inter-electrode distance is kept below 0.5 cm. However the results presented here indicate that surface EMG recordings on RF may not be representative of the activation state of the muscle but may be a summation of signals from RF and VL. It was shown that for knee extension contractions, EMG was recorded on the surface of RF in the absence of fine wire EMG and that the recorded signal originates in the vastii, most likely in vastus intermedius.

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Ciaran Byrne was born in Drogheda, Ireland in 1977. He received a B.Sc. degree in Sport and Exercise Science from the University of Limerick in 1999. In 2002, he received an MSc. degree from the same institution. He is currently employed as a research scientist for BioMedical Research Ltd., an Irish company that develops muscle stimulation products for the sports, health and medical markets. His research interests include muscle stimulation, EMG and strength and conditioning.

Gerard Lyons graduated from University College, Cork, Ireland with a B.E. in Electrical Engineering (First Class Honours) in 1980, and an M.Eng.Sc. Microelectronics in 1982 and graduated from the National University of Ireland, Galway with a Ph.D. in Biomedical Engineering in 2000. From 1985 to 1990 Dr. Lyons worked in the semiconductor industry in the Santa Clara Valley and Monterey Peninsula in California, USA. He returned to Ireland in 1990 and joined the University of Limerick as a member of faculty and is currently a Senior Lecturer in Electronic and Computer Engineering, Assistant Dean, Research, College of Informatics and Electronics and Director of the Biomedical Electronics Laboratory at the university. Dr. Lyons' primary research interests are gait rehabilitation using FES, mobility assessment of the elderly and use of computer-based biofeedback techniques for rehabilitation applications.

Alan E. Donnelly received a B.Sc. degree (with honours) from the University of Strathclyde, Scotland in 1984, and a Ph.D. degree in human muscle physiology from the University of Aberdeen, Scotland in 1988. He then worked as a lecturer at the University of Wolverhampton, England before moving to the University of Limerick. Since 1997 he has been Senior Lecturer in exercise physiology in the department of physical education and sport sciences, where he is also head of department. His research interests include human muscle damage, muscle connective tissue plasticity, and human muscle activation in exercise.

Derek T. O'Keeffe received his B.Eng. degree in electronic engineering (First Class Honours) in 1996, his research M.Eng. (Biomedical) degree in 1998 and his Ph.D degree in Biomedical Engineering in 2001 from the University of Limerick, Ireland. He is currently a member of faculty at the Department of Electronic and Computer engineering, University of Limerick, Ireland and he also holds an adjunct faculty position at the Department of Physical Medicine and Rehabilitation, Harvard Medical School, Boston, USA. His main research interest involves developing embedded systems for the investigation and rehabilitation of clinical biomedical engineering problems (e.g., side-effects of Stroke/Space flight). He is also involved with research investigating the use of the Internet as an e-learning environment and the development of autonomous robots.

Hermie J. Hermens is a biomedical engineer who did his Ph.D. on surface Electromyography analysis and clinical applications. Currently, he is Professor in neuromuscular control at the University of twente and cluster manager in the area of non-invasive neuromuscular assessment at Roessingh Research and Development (Netherlands). He currently supervises 10 Ph.D. students in the areas of his special interest: the use of surface EMG to study motor control in spasticity, gait, chronic pain and functional electrical stimulation. He co-ordinated three European projects, among which the Seniam project on standardisation of surface EMG recording and processing and participated in over 15 other international projects in forementioned areas.

Anand Vishwanath Nene was born in Bombay, India. He received M.B.B.S. and M.S. degrees in 1972 and 1976, respectively, from Bombay University. Soon afterwards he arrived in the United Kingdom. He obtained a further Post-Graduate degree of Master of Orthopaedic Surgery (MChOrth) from the University of Liverpool in 1979. He returned to India in 1983 and worked as an orthopaedic surgeon in Nagpur, India. Circumstances brought him back to the United Kingdom in 1985. From December 1985 to May 1993 he worked as a medical research fellow in the Orthotic Research and Locomotor Assessment Unit (ORLAU) at The Robert Jones and Agnes Hunt Orthopaedic & District Hospital in Oswestry, Shropshire, UK. There he developed his interest in the subjects of human locomotion, paraplegic locomotion, Functional Electrical Stimulation and cerebral palsy. He was invited to work in the Netherlands. In January 1994 he started work as a Research Fellow in Roessingh Research & Development based at Roessingh Rehabilitation Centre in Enschede, The Netherlands. From July 1994 to June 1997 he retrained as a specialist in Physical & Rehabilitation Medicine. In December 1994 he was awarded Ph.D. by Twente University for his thesis on Paraplegic Locomotion.

Presently, he works as a specialist in Physical & Rehabilitation Medicine, and continues to work as a research fellow in Roessingh Research and Development, based at Roessingh Rehabilitation Centre in Enschede, The Netherlands. He has continued his research interests in Functional Electrical Stimulation, Gait Analysis and it's applications in clinical decision making, balance control in neurological disorders and it's relation to walking ability.