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Inter-electrode spacing of surface EMG sensors: Reduction of crosstalk contamination during voluntary contractions

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ABSTRACT

We investigated the influence of inter-electrode spacing on the degree of crosstalk contamination in surface electromyographic (sEMG) signals in the tibialis anterior (target muscle), generated by the triceps surae (crosstalk muscle), using bar and disk electrode arrays. The degree of crosstalk contamination was assessed for voluntary constant-force isometric contractions and for dynamic contractions during walking. Single-differential signals were acquired with inter-electrode spacing ranging from 5 mm to 40 mm. Additionally, double differential signals were acquired at 10 mm spacing using the bar electrode array. Crosstalk contamination at the target muscle was expressed as the ratio of the detected crosstalk signal to that of the target muscle signal. The crosstalk contamination ratio approached a mean of 50% for the 40 mm spacing for triceps surae muscle contractions at 80% MVC and tibialis anterior muscle contractions at 10% MVC. For single differential recordings, the minimum crosstalk contamination was obtained from the 10 mm spacing. The results showed no significant differences between the bar and disk electrode arrays. During walking, the crosstalk contamination on the tibialis anterior muscle reached levels of 23% for a commonly used 22 mm spacing single-differential disk sensor, 17% for a 10 mm spacing single-differential bar sensor, and 8% for a 10 mm double-differential bar sensor. For both studies the effect of electrode spacing on crosstalk contamination was statistically significant. Crosstalk contamination and inter-electrode spacing should therefore be a serious concern in gait studies when the sEMG signal is collected with single differential sensors. The contamination can distort the target muscle signal and mislead the interpretation of its activation timing and force magnitude.

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1. Introduction

Surface electromyographic (sEMG) signals detected with sensors placed on the skin consist of the electrical activity originating from the contracting muscle of interest (target muscle) as well as volume-propagated EMG signals from active neighboring muscles (crosstalk muscles), along with the baseline noise inherent in the recording system and the skin-electrode interface. Crosstalk signals distort the target muscle signal and mislead the interpretation of the activation timing and force magnitude of the target muscle. The amplitude of the crosstalk signal detected at the target muscle site has been documented to be as great as 16% of that of a stimulated crosstalk muscle signal (De Luca and Merletti, 1988; Koh and Grabiner, 1992). This degree of crosstalk contamination is particularly problematic in gait analysis as originally discussed by Perry et al. (1981) for patients with spasticity, and in any activity involving co-activation.

The most influential factors that contribute to the amount of detected crosstalk signal are: the spacing between the electrodes on the sEMG sensor and the location of the sensor on the surface of the muscle. It follows that a sensor placed at the perimeter of a muscle surface will detect greater crosstalk from adjacent muscles than one placed in the center of the muscle surface. For this and other reasons discussed in De Luca (1997), Basmajian and De Luca (1985), and De Luca et al. (2010), it is best to locate the sensor in the middle of the muscle belly.

The common design of sEMG sensors consists of an arrangement of two electrodes placed in proximity, each detecting a potential on the skin. The two potentials are subtracted and amplified, providing a single differential signal, which is more sensitive to the local potentials on the muscle than those originating farther away. As the inter-electrode spacing is increased, the resultant target signal and the crosstalk signal also increase in magnitude. For the target signal this relationship holds until the boundaries of the muscle interfere, or according to Roeleveld et al. (1997) the length of the action

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potentials equals the inter-electrode spacing. Therefore, the inter-electrode spacing must be wisely chosen to maximize the target signal and minimize the crosstalk signal.

A widely referenced report from the Surface EMG for Non-invasive Assessment of Muscles (SENIAM) group proposed a 20 mm inter-electrode spacing for bipolar sEMG sensors (Hermens et al., 2000). The recommendation was based on a survey among the SENIAM group, model simulation results (Blok and Stegeman, 1997), and empirical findings (Roeleveld et al., 1997). The issue of crosstalk was discussed, but left inconclusive, stating that there was no general consensus in the literature regarding the quantity and importance of crosstalk (Hermens et al., 2000). Yet, for two decades prior to the SENIAM report, there had been evidence that crosstalk was an issue of concern (Perry et al., 1981; Zipp, 1982; De Luca and Merletti, 1988; Koh and Grabiner, 1992), with additional evidence reported in the past decade (van Vugt and van Dijk, 2001; Farina et al., 2002; Bogey et al., 2003; Johnson and Radtka, 2006; Barr et al., 2010).

Consequently, this study was performed to investigate the influence of inter-electrode spacing on the magnitudes of crosstalk on the Tibialis Anterior (TA) muscle from the Triceps Surae (TS) muscles during constrained isometric contractions and during walking in young healthy subjects. The approach described herein is likely applicable to other muscle combinations and to other subject populations.

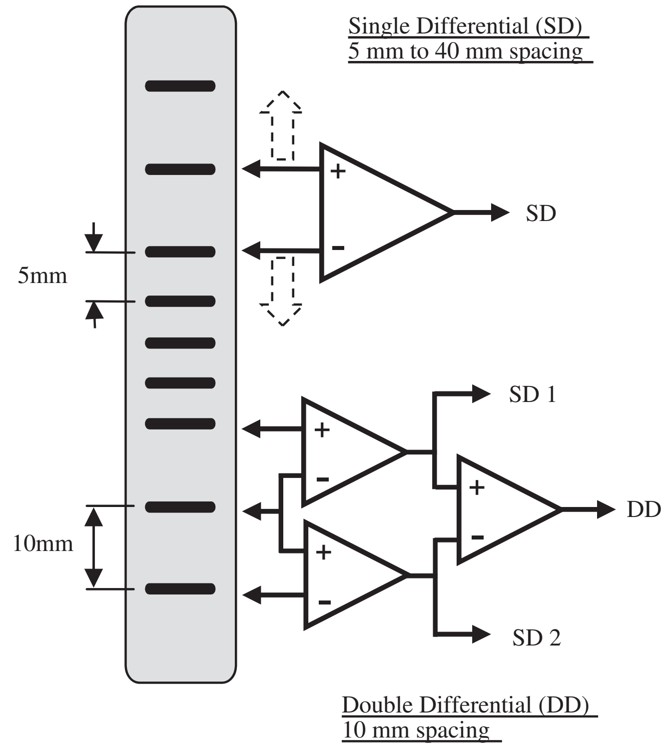

Fig. 1. Examples of the electrical configuration for recording single differential (SD) and double differential (DD) sEMG signals. For the SD configuration, pairs of electrodes along the array were selected to provide inter-electrode spacing ranging from 5 mm to 40 mm. A fixed, 10 mm spacing was used for the DD configuration. For the isometric study, the SD and DD configurations for bars and disks were created in software by subtracting the digitized signals detected from each combination of selected electrodes.

Table 1
Demographic and anthropometric data for crosstalk study.

	Isometric study	Walking study
Males	$n=5$	$n=4$
Females	$n=5$	$n=4$
Age (years)		
Mean (SD)	22 ($\pm$3.1)	23 ($\pm$3.9)
Range	18–27	19–28
Height (cm) (SD)	172.0 ($\pm$7.2)	169.9 ($\pm$9.6)
Mass (kg) (SD)	66.8 ($\pm$8.9)	65.7 ($\pm$11.1)

2. Methods

The TA and TS muscles of the leg were selected for this study because they are of functional importance in gait and balance studies where crosstalk is a serious concern. The subjects were screened for a history of skin and neurological disorders. All volunteered after reading and signing an Informed Consent form approved by an Institutional Review Board. Two studies were executed. In the first study, we investigated the degree of crosstalk contamination during isometric contractions, and in the second study we investigated the degree of crosstalk contamination during walking. A repeated-measures design was used so that in each study subjects were tested with each of the sensor configurations.

Two electrode arrays were constructed. One array consisted of nine, 1 mm wide and 10 mm long, silver-bar electrodes designed to provide an inter-electrode spacing of 5, 10, 15, 20, 25, 30, and 40 mm. The other consisted of four 10 mm diameter silver disks spaced 20 mm apart to provide an inter-electrode spacing of 20 and 40 mm. These arrays were used to provide a series of single differential (SD) and double differential (DD) combinations with different inter-electrode spacing by combining electrodes at different locations along the array. An example of the electrode configuration for the bar array sensor is shown in Fig. 1. The SD bipolar combination represents the commonly used bipolar sensor; the DD combination, first introduced by Broman et al. (1985), differentiates two SD signals to provide a signal that substantially removes far-field potentials such as crosstalk signals. This feature of the DD sensor has been substantiated by De Luca and Merletti (1988), and van Vugt and van Dijk (2001).

2.1. Isometric contraction study

Ten subjects volunteered for the study. Their characteristics are described in the left panel of Table 1. The set-up for the experiment is shown in Fig. 2A. The subjects were seated with their lower limb positioned into a specially designed apparatus that constrained the muscles to isometric contractions by securing the ankle joint at 20° of plantar flexion to minimize muscle pre-tension due to stretch. For details see Adam and De Luca (2005). A force gauge (Interface, Inc. MB-250) measured plantarflexion and dorsiflexion joint torques. Maximal voluntary contraction (MVC) torques for plantarflexion and dorsiflexion were measured by having the subjects perform three contractions as forcefully as possible, with a rest period of 3 min between contractions. The greatest torque value was taken as the value of the MVC.

The recording site was shaved, and the skin was cleansed by mild scrubbing with 70% isopropyl alcohol. The bar array sensor was positioned on the mid-belly of the TA muscle. Potentials from each contact of the array were differentially measured with respect to a common reference electrode placed medially above the tibial bone. Three additional single differential sEMG sensors (DE-2.1 Delsys Inc.) were located on the medial gastrocnemius, the lateral gastrocnemius, and the soleus muscles of the TS, respectively, to monitor their activation state as shown in Fig. 2C.

Two separate sets of contractions were used to generate the crosstalk and target signal activity. The subjects performed isometric contractions at 30, 50, and 80% MVC of plantarflexion to generate crosstalk activity, and at 10, 20, 30, and 50% MVC of dorsiflexion to generate target signal activity. The duration of the contractions ranged from 7 s to 20 s, depending on the contraction level. Three contractions were performed at each force level. A rest period of 1–3 min was included between each contraction to reduce the influence of fatigue.

Signals from all the electrodes of the sensor array were amplified, band-pass filtered (3 dB bandwidth 20–450 Hz), and sampled at 20 kHz using a 16 bit A/D converter. The digitized signals were subtracted via software to create a matrix of SD pair combinations for the selected inter-electrode spacing from 5 mm to 40 mm. DD pair combinations were created for the 10 mm spacing. The resultant SD and DD sEMG signal combinations from all the target muscle and crosstalk muscle contractions were analyzed in the regions where the ankle torque remained within $\pm$5% of the target torque. Time intervals where the TA and the TS muscles were co-activated were determined using the signals detected by the 10 mm DD configuration. These regions were not analyzed because the target and the crosstalk signals could not be distinguished.

The procedure was repeated for the disk array sensor. In this case, only the signals from the 20 and 40 mm inter-electrode spacing were calculated and analyzed because the diameter of the disk precluded smaller inter-electrode spacing.

An additional isometric procedure was performed to investigate differences in sEMG signal amplitude between bar and disk arrays. Data were acquired from the same location on the TA muscle using each array while a subject performed nine 30% MVC contractions of the target muscle and nine 50% MVC contraction of the crosstalk muscle.

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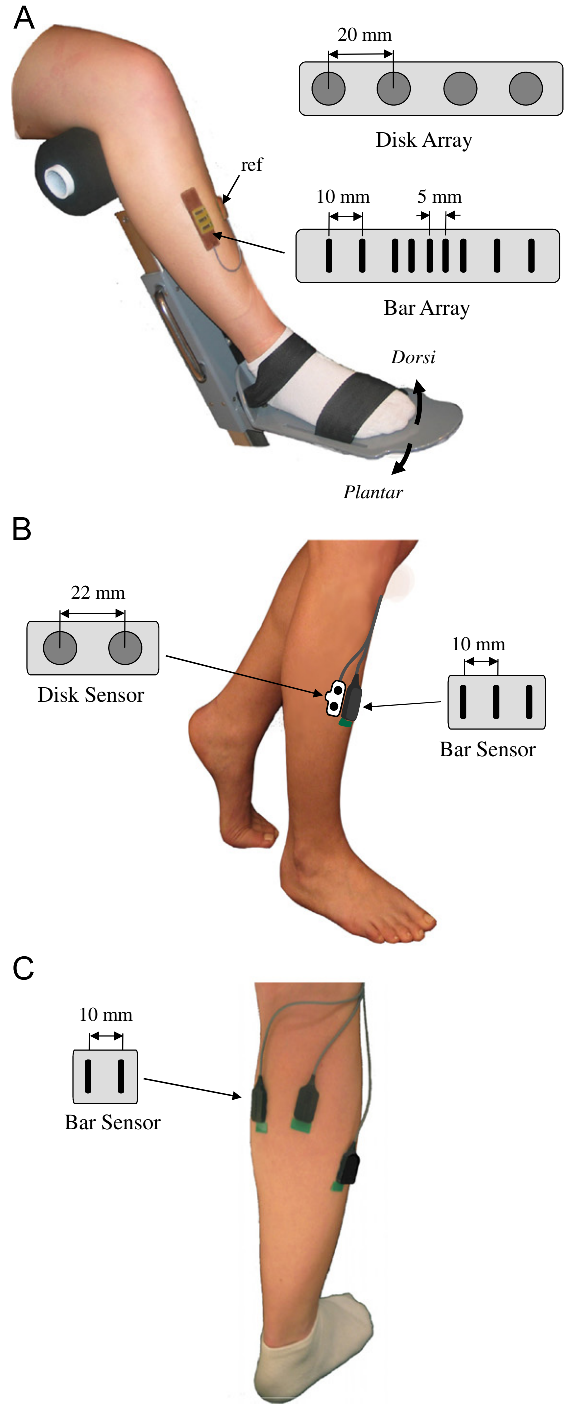

Fig. 2. For the isometric study (diagram A), the lower leg of the subject was positioned in an ankle restraint apparatus, which measured ankle torque during isometric dorsiflexion and plantarflexion contractions. The candidate bar or disk array was positioned on the mid-belly of the tibialis anterior (TA) muscle. For the gait study (diagram B), an sEMG disk sensor with 2 contacts and an sEMG bar sensor with 3 contacts were positioned as shown on the TA muscle. For both studies (diagram C), plantarflexion activity was monitored using three additional 10 mm bar sEMG sensors positioned on the triceps surae (TS) muscle group. (A) Isometric Contraction Study, (B) Gait Study and (C) Monitoring sEMG sensors on Triceps surae (Both Studies).

2.2. Gait study

In these experiments we analyzed the degree of crosstalk present in leg muscles during walking. Eight subjects participated in this study, as described in the right panel of Table 1. sEMG signals were simultaneously recorded from two sensors placed adjacently on the mid-belly of the TA muscle as shown in Fig. 2B. The first was an SD sensor with disks of 10 mm diameter and 22 mm inter-electrode spacing. This commercially available sensor, commonly referred to as having 2 cm spacing, is often used in gait studies. The second was a 3 bar sensor with 10 mm inter-electrode spacing, which provided both SD and DD outputs. The activity of the TS muscle group was monitored using the same setup as shown in Fig. 2C. A pressure sensor was placed under the heel of the subject's foot to identify heel strike events during gait. Before walking, the subject's MVC torque was determined for crosstalk and target contractions using the ankle restraint apparatus. sEMG signals were collected from each of the 8 subjects for a total of 120 steps per subject at a self-selected normal walking speed. The positions of the disk and bar sensors were interchanged after 60 steps to account for effects of electrode location.

3. Results

3.1. Isometric contraction study

Fig. 3 shows the mean and standard deviation values of the RMS amplitude of the sEMG signals from the target muscle and the crosstalk muscles as a function of the inter-electrode spacing for each contraction level. These data were collected with the bar array sensor. The top panels present typical results for 3 trials of data recorded from one subject. The bottom panels show the data selected from 10 subjects normalized to an inter-electrode spacing of 5 mm. The normalized grouped data maintained a curvilinear behavior between signal amplitude and inter-electrode spacing for the target signal, and a linear behavior for the crosstalk signal. Statistical analysis for comparing means was conducted using repeated measures ANOVA. Pair-wise statistical comparisons between the normalized group data for inter-electrode spacing was significant for both the target signal ($p<0.002$) and the crosstalk signal ($p<0.001$) using a Bonferroni pair-wise comparison procedure.

The percentage of crosstalk contamination at the target muscle site was expressed as the ratio of the RMS of the detected sEMG crosstalk signal to that of the target muscle signal. The ratio was calculated for selected combinations of contraction levels for both muscles as shown in Fig. 4A. The sEMG signal detected by the array includes both the crosstalk signal and a baseline noise component. Consideration of the baseline noise component of the crosstalk contamination becomes relevant when the sEMG signal is low, as occurs during low-level contractions or when recording from a differential pair having an inter-electrode spacing of 5 mm. This can be illustrated by subtracting the RMS baseline noise component recorded at 0% MVC from the crosstalk contamination signal as shown in Fig. 4B.

For all contraction ratios, the level of crosstalk contamination increases as the inter-electrode spacing increases from 10 mm to 40 mm, with the highest level ($\sim$50%) occurring at the 40 mm spacing for the 80% MVC crosstalk muscle/10% MVC target muscle ratio. A pair-wise comparison indicated significant inter-electrode spacing effects for each of the contraction ratios ($p<0.002$).

A comparison of the RMS amplitude of the sEMG signal detected by the bar and disk arrays at the 20 mm and 40 mm inter-electrode spacing is presented in Fig. 5A. Pair-wise comparisons between the bar and disk data were not statistically significant for both the target muscle contractions ($p>0.07$) and crosstalk muscle contractions ($p>0.13$). Fig. 5B compares the increase in the sEMG signal amplitude between bar and disk arrays resulting from an increase in inter-electrode spacing from 20 mm to 40 mm. Data were acquired from all 10 subjects. Pair-wise comparisons between the bar and disk data for each of the contraction levels was not statistically significant for target muscle ($p>0.44$) and crosstalk muscle ($p>0.23$) contractions.

3.2. Gait study

Fig. 6 shows the sEMG signals detected from the TA and the gastrocnemius muscles with different sensors. Panel A shows the

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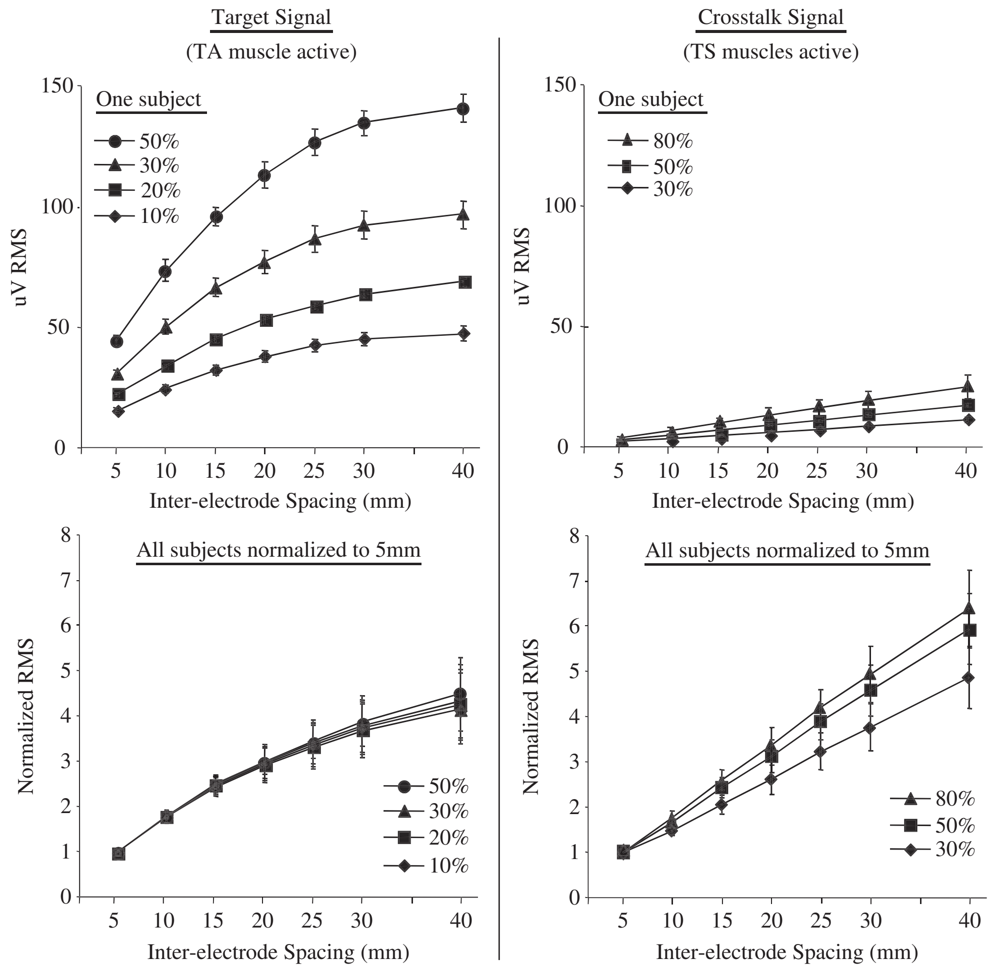

Fig. 3. Plots of the RMS sEMG signal amplitude for the target and crosstalk muscle contractions as a function of inter-electrode spacing. The upper plots of each panel show the means and standard deviations of RMS data for 3 trials recorded from one subject at each % MVC contraction level. The lower plots show the means and standard deviations of the RMS data selected from all subjects normalized to an inter-electrode spacing of 5 mm.

signal from the TA detected with an SD disk sensor; panel B shows the signal from the TA collected with an SD bar sensor; panel C shows the signal from the TA, but detected with a DD bar sensor; and panel D shows the signal from one of the gastrocnemius muscles detected with an SD bar sensor. Subject 1 presented no co-activation, and subject 2 presented a period of co-activation beginning at the heel strike. This is determined by the presence of the sEMG signal from the gastrocnemius muscle in panel D, which co-exists with the sEMG signal from the TA in panel A. For each step, two regions were selected for analysis. The target signal from the TA muscle was analyzed during the swing phase over a period when the crosstalk muscle (gastrocnemius) was inactive. The crosstalk signal was analyzed during the stance phase of the cycle over a period when the target muscle was inactive, as is evident from the DD sensor in panel C. The shaded regions show the periods during each step where the crosstalk muscle was active, as is evident in panel D. The encircled areas highlight the signals recorded from each of the TA sensor configurations during these periods. For subject 2, during the stance phase, target muscle inactivity was determined by the epoch in the encircled area where the DD sensor signal output was quiescent, as is evident in panel C.

The amount of crosstalk generated by the activation of the gastrocnemius, and detected on the target muscle (TA), varies with different sensors. In both examples, the SD disk sensor with 22 mm spacing has the greatest amount of crosstalk signal. The SD bar sensor with 10 mm spacing has a lower amplitude crosstalk signal. The lowest amplitude crosstalk signal is from the DD bar sensor. This effect was found in all 8 subjects.

For each step, the percentage of crosstalk contamination present in the target sEMG signal for each of the three sensor configurations was calculated using the selected periods of target muscle activity and crosstalk muscle activity in each of the three sensors on the TA. The results are shown in Fig. 7. The 22 mm disk, 10 mm bar, and 10 mm DD sensors produced 23%, 17%, and 8% crosstalk contamination, respectively. Pair-wise comparisons between the three sensor types was significant ($p < 0.016$).

4. Discussion

This study established a relationship between inter-electrode spacing and crosstalk signal contamination during isometric contractions and during normal walking.

4.1. Isometric contraction

The first finding of this study is that the amplitude of the sEMG signal obtained from the 10 mm diameter disk electrodes and the 1 mm × 10 mm bar electrodes were not significantly different for the two inter-electrode spacings (20 mm and 40 mm). This was true for signals from the target muscle as well as from the crosstalk muscle for all contractions ranging from 10% to 80% MVC. Therefore, the observations of the crosstalk contamination at 20 mm and

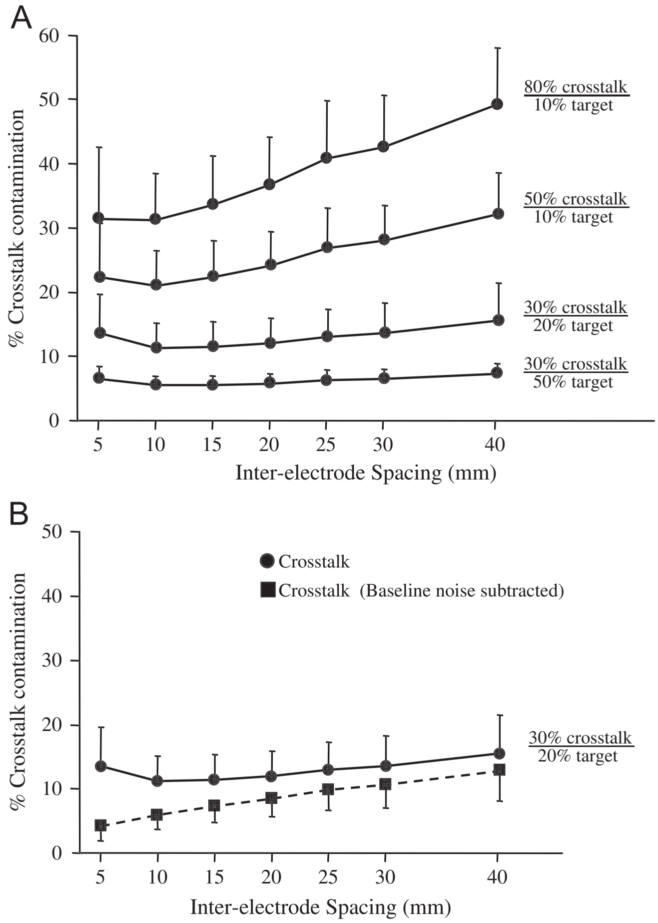

Fig. 4. Plots of the % crosstalk contamination in the target muscle sEMG signal are shown as a function of inter-electrode spacing for different ratios of % MVC crosstalk muscle to % MVC target muscle signal. The upper plot (A) shows the mean and standard deviation of the data selected from all subjects. The lower plot (B) shows a representative example of the % crosstalk contamination for one of the ratios, with and without the contribution from the baseline noise component.

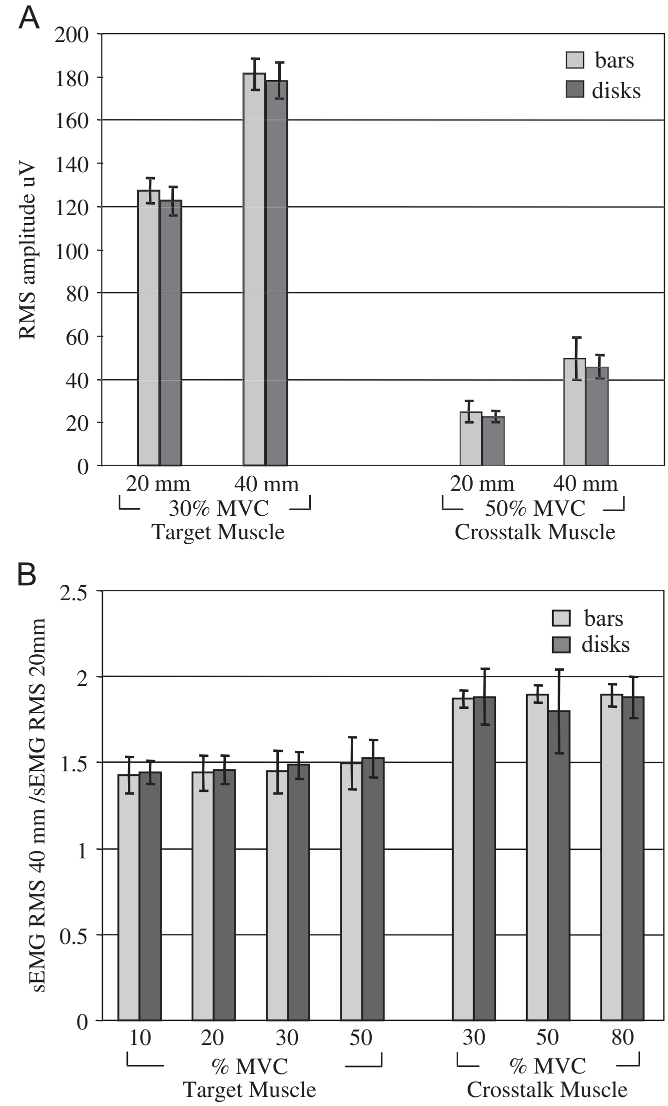

Fig. 5. Comparison of bar and disk array results for different % MVC contraction levels of target muscle and crosstalk muscles. The upper plot (A) is a comparison of the sEMG signal amplitude detected by the bar and disk arrays for inter-electrode spacing of 20 mm and 40 mm from 9 repeated trials at 30% MVC target and 50% MVC crosstalk contraction levels in a normal subject. The lower plot (B) is the ratio of increase in sEMG signal amplitude resulting from an increase in inter-electrode spacing from 20 mm to 40 mm in data selected from all subjects.

40 mm can be considered to be applicable for both bar and disk sensors.

Fig. 3 shows that as the inter-electrode spacing increases, the amplitude of the crosstalk signal increases more than that of the target signal. This signal behavior has been explained by Roeleveld et al. (1997), who attributed it to the source depth and the degree of spatial overlap of the action potentials detected on the skin. It follows that the greater the spacing between the electrodes, the greater the crosstalk contamination.

Fig. 4 shows that for all the investigated ratios of crosstalk and target muscle signal levels during isometric contractions, the smallest observed crosstalk signal (crosstalk sEMG plus baseline noise) was obtained with the 10 mm spacing. This was the optimum inter-electrode spacing for reducing crosstalk in sEMG signals that contain baseline noise.

In the extreme case when the crosstalk muscles (TS) contracted at 80% MVC and the target muscle (TA) at a relatively low 10% MVC, the sEMG signal detected above the TA with an SD bar sensor contained as much as 36% crosstalk contamination at the 20 mm inter-electrode spacing, and up to 49% for 40 mm spacing. Although this is a rare co-activation combination, it does raise worrisome concern. Even at more commonly occurring combinations of co-activation such as 30% MVC crosstalk muscle contraction and 20% MVC target muscle contraction, the target signal contained up to 12% crosstalk at a spacing of 20 mm and 16% for 40 mm spacing.

The 20 mm spacing always provided greater crosstalk contamination than the 10 mm spacing. As the spacing was decreased from 10 mm to 5 mm, the percentage of contamination increased, due to the dominance of the baseline noise component whose amplitude becomes relevant when the target signal is low, as would be the case with the smaller inter-electrode spacing. Hence 10 mm spacing was optimal for reducing crosstalk contamination.

4.2. *Gait*

The results illustrate a critically important point as to why it is necessary to identify or reduce the presence of crosstalk signals. The gray area in Fig. 6 represents the time region where the crosstalk (Gastrocnemius) muscle is active during gait. Without the benefit of the DD bar sensor, the signal in the gray area of the upper two traces could be easily misinterpreted as arising from the target muscle (TA) because the sensors are placed on top of the TA. An example of this is shown in Fig. 6 for subject 1. The large amount of signal recorded from the TA disk sensor

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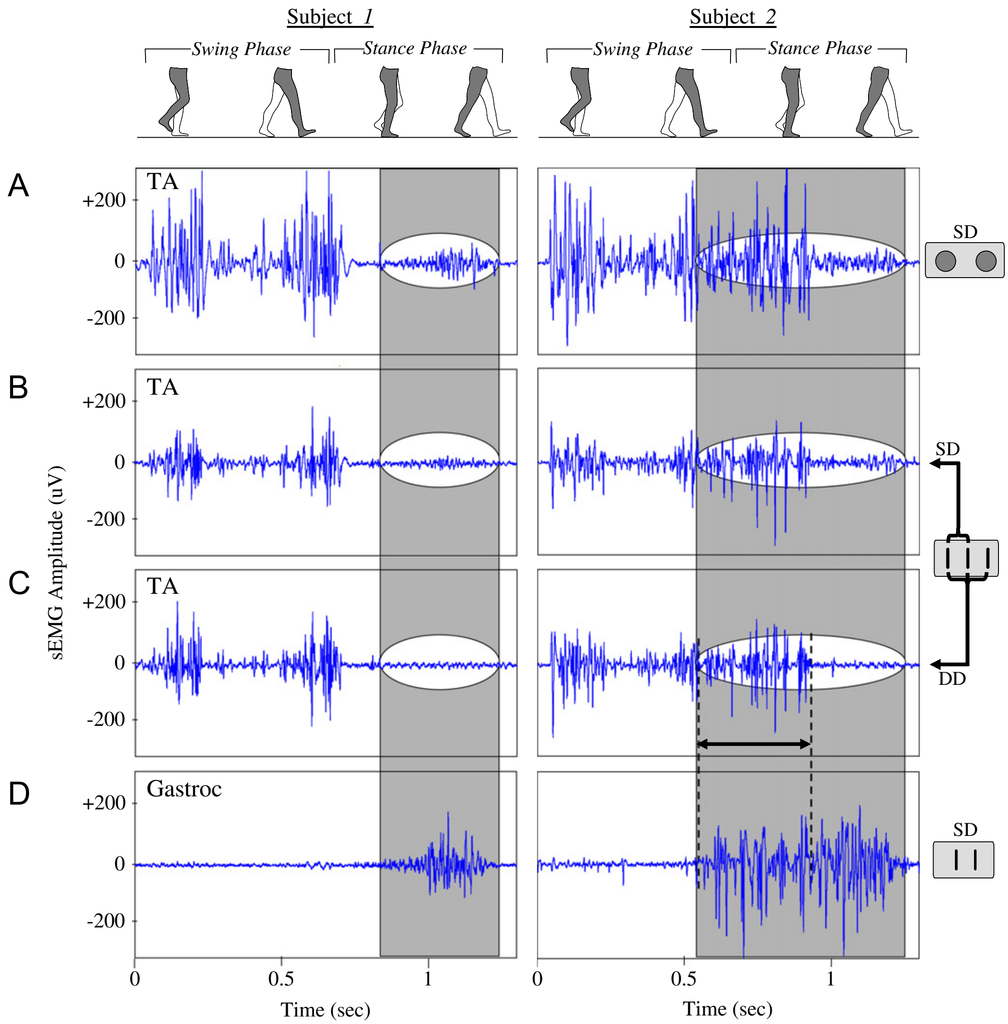

Fig. 6. Examples of sEMG signal cross-talk from different sensor configurations placed on the TA muscle during walking. Data were recorded from two normal subjects; subject 1 without co-contraction, and subject 2 with co-contraction between Gastroc and TA muscles. The upper panel (A) shows the signals recorded from the TA muscle using a 22 mm SD disk sensor. The middle panels (B and C) show the SD and DD signals recorded by a 3 bar sensor, and the lower panel (D) shows the signal recorded from the Gastroc muscle using a 10 mm SD bar sensor. The shaded regions indicate the periods when the Gastroc muscle is active. The encircled areas highlight the signals recorded from each of the TA sensor configurations during these periods. The dotted region shown with the arrow in the lower two plots for subject 2 indicate periods where co-contraction of the TA and Gastroc muscles is present.

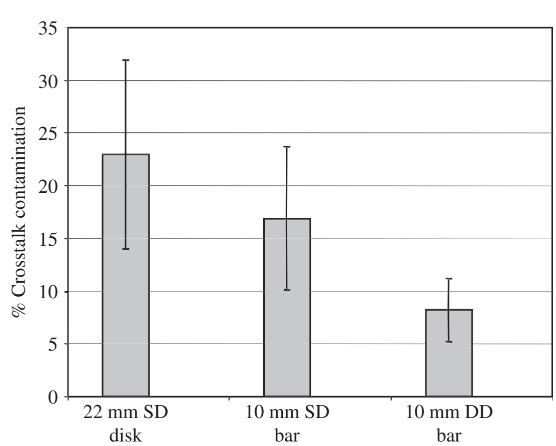

Fig. 7. Comparison of % crosstalk contamination for the three different sensor configurations located on the TA muscle for all normal subjects during walking. The graph shows the means and standard deviations for the 22 mm SD disk, 10 mm SD bar, and 10 mm DD bar sensor configurations.

during Gastrocnemius activation (panel A—gray region) could be misinterpreted as TA activation, instead of the lack of TA activity detected during this period by the DD signal (panel C). For subject 2, the DD sensor shows no signal in the latter half of the gastrocnemius activation (panel C) indicating that during the first half of the gastrocnemius activation, the TA is co-activated, but is quiet during the second half of the gastrocnemius activation. The SD disk sensor (panel A) provides a particularly problematic perspective of the sEMG signal detected from the TA. It indicates that while the gastrocnemius muscle is activated, the TA appears to be continuously activated, with reduced effort in the second half of the apparent co-activation. This would be an incorrect deduction inconsistent with the actual muscle activation. It would lead to incorrect timing of the activation of the TA muscle, and an apparent increase in the activation level of the TA.

Even though the DD bar sensor had the least amount of crosstalk contamination, it did not remove it completely. This limitation is likely due to the paths taken by the crosstalk signal to reach the three bars of the DD sensor that may introduce

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different signal amplitudes and phase lags at each electrode, thereby deteriorating the common mode cancellation.

In conclusion, the 10 mm inter-electrode spacing was found in both studies to be the preferred inter-electrode spacing for reducing crosstalk signals. No significant differences between bar and disks were observed. In the three sensors tested in the gait study, the SENIAM-recommended 20 mm spacing disk sensor provided the largest crosstalk signals, which could be misinterpreted when analyzing muscle activation patterns during gait. For the gait study, the 10 mm double differential (DD) sensor was the most effective sensor for reducing the crosstalk signal.

Conflict of interest statement

Carlo J. De Luca is the President and CEO of Delsys Inc.

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