THE EFFECT OF BREAST SUPPORT ON UPPER BODY MUSCLE ACTIVITY DURING 5 KM TREADMILL RUNNING

Alexandra Milligan[a], Chris Mills[a], and Joanna Scurr[a]

[a]Department of Sport and Exercise Sciences, Spinnaker Building, University of Portsmouth, PO1 2ER

Corresponding author:
Dr Alexandra Milligan
Department of Sport and Exercise Science
University of Portsmouth
Spinnaker Building
Cambridge Road
Portsmouth
PO1 2ER
United Kingdom
T: +44 (0)2392 84 3085

ABSTRACT

Breast support has previously been shown to influence surface EMG of the pectoralis major during running. Reductions in muscle activity have previously been associated with a reduction in energy cost, which may be advantageous for female runners. Ten female participants performed two self-paced (average pace 9 km·h^{-1}) five kilometre treadmill runs under two breast support conditions (low and high); an additional bare-breasted two minute run was also conducted. Surface EMG electrodes were positioned on the pectoralis major, anterior deltoid, medial deltoid, and upper trapezius, with data collected during the first two minutes of running and each kilometre interval thereafter. Reductions in peak EMG of the pectoralis major, anterior and medial deltoid were reported when participants ran in the high breast support during the initial intervals of the run (up to the second kilometre). The increased activation in the pectoralis major, anterior and medial deltoid in the low breast support may be due to increased tension within these muscles, induced by the greater breast pain experienced in the low breast support. This may be a strategy to reduce the independent breast movement causing the pain through increased muscular activation. This study further promotes the use of a high breast support during running with potential benefits for treadmill running associated with reductions in muscular demand during a five kilometre run.

Key words: Electromyography, sports bra, female runners

Word count: 3706

1.0 Introduction

The electromyographical profile and characteristics of lower body muscles during running has been extensively researched (Gazendam & Hof, 2007; Rand & Ohtsuki, 2000; Yokozawa, Fujii, & Ae, 2007). However, the study of electromyography (EMG) in the upper body during running has received considerably less attention (Newton et al., 1997; Smoliga, Myers, Redfern, & Lephart, 2010). Furthermore, there are even fewer studies which explore EMG of the upper body during running in female participants. When considering the additional mass and magnitude of soft tissue movement of the breast for female runners (Scurr, White, & Hedger, 2010a; Haake and Scurr, 2010; McGhee, Steele, Zealey, & Takacs, 2012), a question that remains unanswered is whether this additional mass and independent soft tissue movement affects the recruitment of motor units and the magnitude of myoelectric activity of muscles of the upper body. A 34D cup (for international bra sizing readers are referred to McGhee and Steele, 2006) participant has an approximated breast mass of 460 g per breast (Turner & Dujon, 2005), and may experience vertical breast displacement up to 80 mm (McGhee, Steele, Zealey, & Takacs, 2012; Scurr, White, & Hedger, 2009) when unsupported during treadmill running. However, the effect of this additional wobbling mass on the neuromuscular system during running has received little attention.

Complaints of muscular discomfort and pain in the neck, back and shoulders are common for women with larger breasts (Letterman & Schurter, 1980; Harbo, Jorum, & Roald, 2003). In order to understand the effect of a breast mass on the musculoskeletal system, Bennett (2009) measured upper body muscle activity of 22 female participants (12 participants defined as a control group with bra sizes from A to C cup, and 10 participants defined as larger breasted with bra sizes > a D cup), during a range of postural tasks such as step ups, sitting and picking up a pencil. Higher percentages of muscle activation were reported in females with larger breasts when compared to smaller cup sizes during these postural trials. Bennett (2009) postulated that the increased activation of upper body muscles for females with larger breasts provides evidence of increased tension in these muscles due to the additional mass of the breasts. In addition to the postural trials it is important to consider how relative movement of the breast mass affects the muscles of the upper body during dynamic tasks, such as running, and what impact this may have on the neuromuscular system during physical activity.

Currently only one abstract is presented in the area. During two minutes of treadmill running, Scurr, Bridgman, and Hedger (2010b) reported no difference in integrated EMG (*i*EMG) of the upper and lower trapezius, anterior deltoid, and erector spinae across different breast support conditions. However, significant reductions in *i*EMG were reported in pectoralis major activity when running in an everyday bra compared to a bare-breasted condition. Matousek, Corlett, and Ashton (2014) describe the anatomical structure and connections between the breast tissue and the pectoralis major muscle, and state that the pectoralis fascia provides anatomical support to the breast's projected suspensory ligaments, nerves, and blood vessels that pass through the retromammary space and attach onto the fascia of the pectoralis major. Based upon the anatomical connection between the breast and the pectoralis major muscle, Scurr et al. (2010b) proposed that the reduction in muscle activity when running in this breast support may be beneficial for female performers, and interestingly suggested the results may indicate that the pectoralis major may contribute to the anatomical support of the breast.

The findings of Scurr et al. (2010) are novel and important to this research area, however, it is established that females will commonly run for durations exceeding two minutes, and it is unlikely that a physiological or biomechanical steady state would have been reached within two minutes of running (Hardin, Van Den Bogert, & Hamill, 2004;

Lavcanska, Taylor, & Schache, 2005). Consequently these data may not be representative of the biomechanics of a female runner. Therefore, the potential performance implications of reductions in muscle activity associated with increasing breast support were not considered within this study.

Examining the amplitude (peak RMS) and total (*i*EMG) muscle activity in the upper body during running in different breast support conditions will increase the understanding of the effect of breast support on the neuromuscular system during running. Therefore, the aim of the study was to examine the effect of breast support on upper body myoelectric activity during a five kilometre run. Firstly, it was hypothesised that upper body muscle activity would be significantly reduced in the high breast support condition, when compared to the low and bare-breasted support conditions. Secondly, it was hypothesised that there would be no differences in upper body muscle activity across the five kilometre run.

2.0 Methods

2.1 Participants

Following institutional ethical approval, ten regularly exercising female volunteers, (experienced treadmill and outdoor runners currently training ≥ 30 min, ≥ five times per week) participated in this study. Participants had not had any children, not experienced any surgical procedures, and were of a 34D or 32DD bra size (for international sizing readers are referred to McGhee & Steele, 2006). Participants were bra fit using the best-fit method recommended by White and Scurr (2012). All participants provided written informed consent to participate in this study and had a mean (SD) age of 23 years (2 years), body mass 62.1 kg (5.4 kg), and height 1.60 m (0.05 m).

2.2 Procedures

In a random order, two five kilometre treadmill runs (h/p/cosmos, Germany) were performed on separate days (up to 72 hours apart); once in a low breast support (Everyday, non-padded, underwired t-shirt bra, made from 88% polyamide and 12% elastane lycra) and once in a high breast support (Sports bra made from 57% polyester, 34% polyamide, and 9% elastane). Participants wore the same lower body clothing and footwear for both treadmill runs. Participants selected a comfortable running speed, which they maintained for both five kilometre runs (without adjustment). The average speed (± SD) across all participants was 9 $km \cdot h^{-1}$ (1 $km \cdot h^{-1}$). Participants were required to perform an additional bare-breasted (BB) treadmill run, but due to the discomfort associated with this condition, participants ran without breast support for only two minutes (Scurr et al., 2009; 2010a; McGhee, Steele, Zealey, & Takacs, 2012). Within each support condition, participants were asked to provide a rating of breast pain after two minutes of running and once more at the end of the five kilometre run, using an adapted version of the numerical visual analogue scale presented in Mason, Page, and Fallon (1999), a zero to ten scale (0 = no pain, 5 = moderate pain, and 10 = excruciating pain). The temperature within the laboratory was set to 20°C between participants and support conditions, to keep the participants as thermally comfortable as possible and to reduce the onset of perspiration.

2.3 Electromyography

Electromyography data were collected using an eight channel Datalink EMG system (Biometrics, UK). In accordance with the SENIAM recommendations, electrodes were positioned parallel with the muscle fibres and on the muscle bellies (De Luca, 1997) of the pectoralis major (positioned at the pars clavicularis), anterior and medial deltoid, and upper trapezius on the right side of the body (Figure 1).

- INSERT FIGURE 1 HERE –

To reduce skin impedance, the skin was shaved and cleansed with an isopropyl alcoholic swab (Medi-Swab, UK) (De Luca, 1997). Biometrics SX230 active (Ag/AgCl) bipolar pre-amplified disc electrodes (gain x 1000; input impedance >100 MΩ; common mode rejection ratio >96dB; with a 1 cm electrode contact surface, and 2 cm separation distance) were adhered to the site using a hypoallergenic adhesive tape (3M, UK) (De Luca, 1997). Electromyography signals were sampled at 1000 Hz. A passive reference electrode was positioned on the olecranon process. The Datalink utilised both high-pass filter (18 dB/octave; <20 Hz) to remove DC offsets, and low pass filter for frequencies >450 Hz. The electrodes included an eighth order elliptical filter (-60 dB at 550 Hz). The Datalink system was zeroed before any data were collected, this involved the participants lying supine and relaxing all muscles. Once completed, the electrode placement was verified by voluntary muscle actions. The electrodes were secured with clinical tape to reduce relative movements of the electrodes during running. Data were collected over ten second intervals at the end of the first two minutes of running, and at each kilometre interval thereafter.

2.4 Data processing

Raw EMG signals (mV) were visually checked for artefacts and then processed using two processing techniques; (1) RMS (filter constant of 100 ms) (McLean, Chislett, Keith, Murphy, & Walton, 2003; St-Amant, Rancourt, & Clancy, 1996), and (2) full-wave rectified, followed by an *i*EMG (filter mV.s) performed over every sample. Processing techniques were employed to the raw data separately, for five gait cycles at each interval of the five kilometre run. This was conducted for each muscle (four muscles) under each breast support condition. The processed EMG signals (RMS and *i*EMG) were normalised using a form of the peak dynamic method, using the bare-breasted data as the denominator (Scurr et al., 2010b); based on the assumption that the peak RMS and *i*EMG values would be reported under the bare-breasted condition for each muscle. Within each breast support conditions, the peak values from five gait cycles (n=5) at each distance interval (n=6), for each muscle (n=4) were quantified as a percentage of the denominator (the peak EMG value under the bare-breasted condition, within a gait cycle) (Burden, Trew, & Baltzopoulos, 2003).

2.5. Statistical analysis

All data were checked for normality (Kolmogorov-Smirnov and Shapiro-Wilk) and homogeneity of variance (Mauchly's test of Sphericity), and parametric assumptions assumed where $p > .05$. One-way and two-way repeated measures ANOVAs with *post hoc* pairwise comparisons (with Bonferroni adjustment) were performed to assess the effect of breast support on EMG activity across the intervals of the five kilometre run. Non-parametric Friedman tests of difference were employed to assess any differences in exercise-related breast pain within and between the breast support conditions. *Post hoc* Wilcoxon comparisons were employed to determine where the differences lay. Effect size (η^2) and observed power (1-β) were calculated to characterise the strength of the results, where a small effect = < .10, a medium effect = < .30, a large effect = > .50, and a high power = >.80 (Field, 2009).

3.0 Results

3.1 Pectoralis major

During the first two minutes of running, peak RMS pectoralis major activity was significantly reduced in the high breast support when compared to the bare-breasted and low support conditions, reductions of 30% and 29%, respectively (Table 1). At the fourth kilometre of the five kilometre run, the peak RMS pectoralis major activity was reduced by 45% when the participants wore the high breast support compared to the low breast support.

- INSERT TABLE 1 HERE –

No differences were reported in the *i*EMG pectoralis major muscle activity between breast support conditions. The surface EMG of this muscle did not differ within either breast support over the intervals of the five kilometre run.

3.2 Anterior deltoid

Surface EMG of the anterior deltoid was significantly affected by the breast support worn during treadmill running, with significant reductions in peak RMS activity when wearing the high breast support compared to the lower breast support conditions. However, these differences were only reported during the first two minutes of running. Running without external breast support elicited greater peak RMS values (60% more) when compared to the high breast support condition.

- INSERT TABLE 2 HERE –

The *i*EMG of the anterior deltoid was found to increase from the first two minutes to the fourth kilometre of the five kilometre run in both the low and high breast support conditions, increasing by 12% and 57%, respectively.

3.3 Medial deltoid

During the first two minutes of running, the high breast support significantly reduced peak RMS activity of the medial deltoid when compared to the bare-breasted and low breast support conditions. Peak RMS activity of the medial deltoid remained lower when participants wore the high breast support, when compared to the low breast support, during the first and second kilometre intervals.

- INSERT TABLE 3 HERE –

No change in EMG of the medial deltoid was reported within either breast support condition over the intervals of the five kilometre run.

3.4 Upper Trapezius

Muscle activity in the upper trapezius was not affected by the breast support worn during treadmill running. Furthermore, no changes were reported over the intervals of the five kilometre run.

- INSERT TABLE 4 HERE –

3.5 Breast pain ratings

Exercise-related breast pain was significantly different between the three breast support conditions during the first two minutes of running (χ^2 (2) = 20.000, *p* = .001), with the bare-breasted support eliciting greater breast pain than the low (*p* = .005) and high (*p* = .005) breast support conditions (Table 5). Furthermore, the high breast support significantly reduced the exercise-related breast pain compared to the low breast support during the two minute (*p* = .005), and five kilometre treadmill run (*p* = .009). Interestingly, the participants rated their exercise-related breast pain as significantly greater in the low breast support during the first two minutes when compared to their five kilometre rating (*p* = .016). However, no differences were reported between the first two minutes and the five kilometre rating when participants wore the high breast support.

- INSERT TABLE 5 HERE -

4.0 Discussion

This is the first study to consider the effect of breast support on upper body muscle activity during a five kilometre treadmill run. Within the current study, wearing a high breast support significantly reduced the peak RMS activity of the pectoralis major, anterior deltoid, and medial deltoid during the initial stages of a five kilometre run.

The greatest movement of the breast during running was expected and reported within the bare-breasted condition (Scurr et al., 2009; 2010a; White et al., 2009). Within the current study, the increase in pectoralis major activity during the bare-breasted condition is of interest. The majority of previous literature examining the role of muscles for damping the vibrations and movement of soft tissue has been conducted in the lower extremities, reporting that greater muscle activity reduces the soft tissue movement (Wakeling, Liphardt, & Nigg, 2003; Wakeling, Nigg, & Rozitis, 2002). Therefore, it is interesting to see the opposite relationship shown with the soft tissue of the breast and the pectoralis major muscle. The connection site of the breast to the pectoralis major is unique, and cannot be directly compared to the soft tissue previously explored in the lower limbs. It is suggested that the decrease in pectoralis major and deltoid activity reported in the high breast support may be due to less tension within the upper body when running with superior breast support, due to the significant reduction in breast pain. In line with previous literature (Mason et al., 1999; McGhee, Power, & Steele, 2007; Scurr, et al., 2010a; White et al., 2009; McGhee et al., 2012), exercise related breast pain was significantly greater in the bare-breasted trial and low breast support than the high breast support. However, the pectoralis major muscle activity was greater within the lower breast support conditions. Interestingly, ratings of breast pain were significantly less at the five kilometre interval than the first two minutes of running in the low breast support condition. When participants experienced breast pain, tension might increase in the musculature of and around the torso, which increases the activation (as seen in the first three intervals of the run), as a strategy to prevent the breast movement causing the pain.

Hamdi, Würinger, Schlenz, and Kuzbari, (2005) and Matousek, Corlett, and Ashton (2014) stated that the pectoralis fascia provides support to the breast's projected suspensory ligaments, nerves, and blood vessels that pass through the retromammary space and attach onto the fascia of the pectoralis major. In addition, Hamdi et al. (2005) suggested breast parenchyma (glandular tissues) can accompany these tissues to the pectoralis major muscle itself. When considering the anatomical connection between the breast tissues and the pectoralis muscle, the reported increase in pectoralis major activity in the lower breast support conditions may be a protective response to reduce any potential damage to the breast tissues. Therefore, it is postulated that any tension placed on the nerves and ligaments of the breast (caused by independent breast movement), which attach onto the pectoralis major, may elicit greater activation in the pectoralis major muscle.

The deltoid muscle drives movement of the upper arm at the glenohumeral joint, with the anterior and medial fibres supporting abduction at the shoulder (Smoliga et al., 2010), and the anterior deltoid assists the pectoralis major during shoulder flexion (Blasier, Soslowsky, Malicky, & Palmer, 1997). Significant reductions in peak RMS values of these muscles may conserve energy though a reduction in metabolic cost. Previous work within breast biomechanics has suggested that changes in running mechanics may be prevalent in different breast support conditions (White, Scurr, & Smith, 2009; Shivitz, 2001; Boschma, Smith, & Lawson, 1995). It is speculated that the decreased activation of these three muscles in the high breast support may be associated with alterations in the kinematics of the segments these muscles control (e.g. shoulder abduction and flexion). In contrast, it is important to also consider that an individual's running kinematics may remain unchanged, whilst utilising different muscle activation patterns, both of which may have a detrimental impact upon running (e.g. energy cost). In order to progress this research and address this question, future studies could monitor muscle activation patterns and running kinematic parameters simultaneously in different breast support conditions.

During running the upper trapezius supports the glenohumeral joint, incorporating elevation of the scapular and humerus, and assists with humerus adduction during arm swing (Basmajian & De Luca, 1985). Fernandez, Ballestros, Buchthal, and Rosenfalck (1965) reported continual electrical activity from the upper aspect of the trapezius during the gait cycle. Furthermore, the trapezius muscle assists the latissimus dorsi with the upright posture during static and dynamic activities. Due to the trapezius' important postural and functional roles during running, it is unsurprising that this upper body muscle was the most active during the running gait cycle within this study. It was expected that any differences in the EMG signal of the trapezius muscle, between breast support conditions, may indicate alterations to upper body posture including the position and kinematics of the glenohumeral joint, scapula and upper arm, or increased tension in this region elicited by the magnitude of breast movement and breast pain. However, no differences were reported in surface EMG of the upper trapezius between breast support conditions, suggesting that the demand placed upon this muscle remained the same regardless of which breast support is worn. When interpreting the upper trapezius muscle activity it is important to consider the influence the high breast support strap might have had on the data. The racer back strap configuration of the high breast support may have resulted in compression on the upper trapezius electrode, which may have influenced the EMG signal and is highlighted as a limitation to examining this muscle with breast support with a racer back strap configuration. Based upon these findings, hypothesis one can be accepted for the pectoralis major, and anterior and medial deltoid, and rejected for the upper trapezius muscle.

The anterior deltoid was the only muscle to demonstrate a change in surface EMG from the start to the end of the five kilometre run, with the *i*EMG of this muscle shown to increase in both low and high breast support conditions. It has previously been stated that an observed increase in *i*EMG at a constant intensity is the result of additional recruitment of muscle fibres due to the decreased force output associated with fatigue (Abrabadzhiev, Dimitrov, Dimitrova, & Dimitrov, 2010). However, no differences were reported over the five kilometre run in the remaining investigated muscles. The training status of the participants was an important selection criterion, and therefore, significant muscular fatigue was not expected. Based upon these findings hypothesis two is accepted. It is important to consider the magnitude and sources of variance in the EMG signal when considering the reported increases within the anterior deltoid, with 57% and 39% coefficient of variation reported in the low and high breast support, respectively. Two potential sources of noise that may contribute to the signal to noise ratio that could not be filtered include; soft tissue movement around the shoulder joint and the electrode placed on the anterior deltoid, and the onset of perspiration on the skin's surface, under the electrode. It has been shown that perspiration under the surface electrode can dampen the amplitude of the EMG signal (Ray and Guha, 1983), and may filter the high frequency components (De Luca, 1997) by altering the signal through the sweat layer. However, with a significant increase in the anterior deltoid signal during the five kilometre run, it is suggested that the perspiration on the skin's surface did not significantly dampen the EMG signal.

Within the current study soft tissue movement artefact and potential increase in low-pass filtering, due to the volume of breast tissue between the pectoralis major and electrode, was an important consideration for the pectoralis major data collection during running. The electrode placement for the pectoralis major muscle was positioned at the pars clavicularis in an attempt to reduce the potential influence of the breast tissue on this muscle signal.

Recommendations for the pectoralis major electrode placement are sparse in the literature; Król, Sobota, and Nawrat (2007) examined the effect of electrode placement on the pectoralis major and proposed that to achieve the greatest EMG signal, the electrode should be positioned medially on the abdominalis part of the muscle; however these data were collected from male participants and examined during an isometric barbell bench press. Currently no papers detail the influence of breast tissue on the output EMG signal from different sites of the pectoralis major for female participants during dynamic exercises. These data would be extremely beneficial for this area of research, with standardised electrode placement likely to reduce the chance of variability among these data.

5.0 Conclusion

The current study identified changes in pectoralis major, anterior and medial deltoid activity across breast support conditions, with the high breast support reducing muscular activation during running. The anterior deltoid was the only muscle to demonstrate a significant increase in *i*EMG during the five kilometre run. Breast pain ratings significantly decreased at the end of the five kilometre run within the low breast support condition. The findings of this study further promotes the use of a high breast support (sports bra) for female runners, and indicates reductions in peak EMG of three upper body muscles during a five kilometre run when wearing this breast support.

Acknowledgements

The authors would like to acknowledge Shock Absorber UK for providing the funding which enabled this research to be conducted. Furthermore, thanks go to the technical support and participants involved in this research.

References

Abrabadzhiev, T.I., Dimitrov, V.G., Dimitrova, N.A., & Dimitrov, G.V. (2010). Interpretation of EMG integral or RMS and estimates of “neuromuscular efficiency” can be misleading in fatiguing contraction. *Journal of Electromyography and Kinesiology*, 20, 223-232.

Basmajian, J.V., & De Luca, C.J. (1985). *Muscles Alive: their functions revealed by electromyography*. (5th ed). Williams & Wilkins: Baltimore.

Bennett, M. (2009). Differences in upper body posture and postural muscle activation in females with larger breast sizes. [Masters Thesis]. Boise State University, Idaho: USA.

Blasier, R.B., Soslowsky, L.J., Malicky, D.M., & Palmer, L.J. (1997). Posterior glenohumeral subulaxation: Active and passive stabilization in a biomechanical model. *The Journal of Bone and Joint surgery, Incorporated*, 79(3), 433-440.

Boschma, A.C., Smith, G.A., & Lawson, L. (1995). Breast support for the active woman: relationship to 3D kinematics of running [Masters dissertation]. Corvallis, Oregon: Oregon State University.

Burden, A.M. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *Journal of Electromyography and Kinesiology*. 20, 1023-1035.

Burden, A.M., Trew, M., & Baltzopoulos, V. (2003). Normalisation of gait EMGs: a re-examination. *Journal of Electromyography and Kinesiology*, 13, 519-532.

Clarys, J.P. (2000). Electromyography in sports and occupational settings: an update of its limits and possibilities. *Ergonomics,* 43(10), 1750-1762.

De Luca, C. (1997). The use of electromyography in biomechanics. *Journal of Applied Biomechanics*, 13, 135-163.

Fernandez Ballestros, M., Buchthal, F., & Rosenfalck, P. (1965). The pattern of muscular activity during the arm swing of natural walking. *Acta.Physiologica Scandinavica*, 63, 296-310.

Dimitrova, N.A., & Dimitrov, G.V. (2003). Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology*, 13, 13-36.

Gazendam, M., & Hof, A.L. (2007). Averaged EMG profiles in jogging and running at different speeds. *Gait and Posture,* 25, 604-614.

Haake, S., & Scurr, J. (2010). A dynamic model of the breast during exercise. *International Sports Engineering Association*, 12, 189-197.

Hamdi, M., Würinger, E., Schlenz, I., & Kuzbari, R. (2005). Anatomy of the breast: a clinical application. In *Vertical Scar Mammaplasty* (pp. 1-8). Springer Berlin Heidelberg.

Harbo, S., Jorum, E., & Roald, H. (2003). Reduction Mammaplasty: A Prospective Study of Symptom Relief and Alterations of Skin. *Plastic and Reconstructive Surgery*, 111 (1), 103-110.

Hardin, E., Van Den Bogert, A., Hamill, J. (2004). Kinematic adaptations during running: Effects of footwear, surface, and duration. *Medicine and Science in Sports Exercise,* 36(5), 838-844.

Kŕol, H., Sobota, G., & Nawrat, A. (2007). Effect of electrode position on EMG recording in pectoralis major. *Journal of Human Kinetics*, 17, 105-112.

Lavcanska, V., Taylor, N.F., & Schache, A.G. (2005). Familiarization to treadmill running in young unimpaired adults. *Human Movement Science*, 24, 544-557.

Letterman, G., & Schurter, M. (1980). The Effects of Mammary Hypertrophy on the Skeletal System. *Annals of Plastic Surgery,* 5(6), 425-431.

Lowery, M.M., & O'Malley, M.J. (2003).Analysis and simulation of changes in EMG amplitude during high-level fatiguing contractions. *IEEE Transactions on Biomedical Engineering,* 50(9), 1052-1062.

Mason, B.R., Page, K., & Fallon, K. (1999). An analysis of the movement and discomfort of the female breast during exercise and the effects of the breast support in three case studies. *Journal of Science and Medicine in Sport,* 2, 134-144.

Matousek, S.A., Corlett, R.J., & Ashton, M.W. (2014). Understanding the fascial supporting network of the breast: key ligamentous structures in breast augmentation and a proposed system of nomenclature. *Plastic Reconstruction Surgery,* 133(2), 273-281.

McLean, L., Chislett, M., Keith, M., Murphy, M., & Walton, P. (2003). The effect of head position, electrode site, movement and smoothing window in the determination of a reliable maximum voluntary activation of the upper trapezius muscle. *Journal of Electromyography and Kinesiology,* 13, 169- 180.

McGhee, D.M., & Steele, J.R. (2006). How does respiratory state and measurement method affect bra size calculations? *British Journal of Sports Medicine,* 40(12): 970-974.

McGhee, D.E., Power, B.M., & Steele, J.R., (2007). Does deep water running reduce exercise-induced breast discomfort? *British Journal of Sports Medicine*, 41, 879-883.

McGhee, D., Steele, J., Zealey, W., & Takacs, G. (2012). Bra-breast forces generated in women with large breasts while standing and during treadmill running: Implications for sports bra design. *Applied Ergonomics*, 44(1), 112-118.

Newton, R. U., Murphy, A.J., Humphries, B.J., Wilson, G.J., Kraemer, W.J., & Häkkinen, K. (1997). Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *European Journal of Applied Physiology*, 75, 333-342.

Rand, M.K, & Ohtsuki, T. (2000). EMG analysis of lower limb muscles in humans during quick change in running directions. *Gait and Posture*, 12, 169-183.

Ray G.C, & Guha S.K. (1983). Equivalent electrical representation of the sweat layer and gain compensation of the EMG amplifier. *Biomedical Engineering*, 30(2), 130–132.

Scurr, J., White, J., Hedger, W. (2009). Breast displacement in three dimensions during walking and running gait cycles. *Journal of Applied Biomechanics*, 25, 322-329.

Scurr, J.C., White, J.L., & Hedger, W. (2010a). The effect of breast support on the kinematics of the breast during the running gait cycle. *Journal of Sport Sciences*, 29(1), 55-61.

Scurr, J., Bridgman, C., & Hedger, W. (2010b). The influence of breast support on upper body muscle activity during treadmill running. In the 15th Annual Congress of the European College of Sport Science. (edited by F. Korkusuz, H. Ertan, and E. Tsolakidis). Antalya, Turkey: ECSS. pp. 77.

Shivitz, N.L. (2001). Adaptation of vertical ground reaction force due to changes in breast support in running. Unpublished Masters dissertation. Corvallis, Oregon: Oregon State University.

Smoliga, J.M., Myers, J.B., Redfern, M.S., & Lephart, S.M. (2010). Reliability and precision of EMG in leg, torso and arm muscles during running. *Journal of Electromyography and Kinesiology*, 20, e1-e9.

St-Amant, Y., Rancourt, D,, & Clancy, E. (1996). Effect of smoothing window length on RMS EMG amplitude estimates. Bioengineering Conference, 1996, Proceedings of the 1996 IEEE Twenty-Second Annual Northeast.

Turner, A.J., & Dujon, D.G. (2005). Predicting cup size after reduction mammaplasty. *British Journal of Plastic Surgery*, 58, 290-298.

Wakeling, J.M., Nigg, B.M., & Rozitis, A. (2002). Muscle activity damps soft tissue resonance that occurs in response to pulsed and continuous vibrations. *Journal of Applied Physiology*, 92, 1093-1103.

Wakeling, J.M., Liphardt, A., & Nigg, B.M. (2003). Muscle activity reduces soft-tissue resonance at heel-strike during walking. *Journal of Biomechanics*, 36, 1761-1769.

White, J., Scurr. J. and Smith, N. (2009). The effect of breast support on kinetics during over-ground running performance. *Ergonomics.* 52, 492-498.

White, J. & Scurr, J. (2012). Evaluation of the bra fitting criteria for bra selection and fitting in the UK. *Ergonomics*, 55(6), 704-711.

Yokozawa, T., Fujii, N., & Ae, M. (2007). Muscle activities of the lower limb during level and uphill running. *Journal of Biomechanics*, 40, 3467-3475.

Tables

Table 1. Mean (SD) normalised (%) peak RMS and *i*EMG of the pectoralis major during the two minute and five kilometre treadmill run trials, in three breast support conditions.

Intervals	RMS (%)			*i*EMG (%)		
	BB	LOW	HIGH	BB	LOW	HIGH
2 minutes	82 ± 11*[ab]	81 ± 27*[ac]	58 ± 39*[bc]	75 ± 7	93 ± 26	85 ± 33
1 km		71 ± 27	55 ± 35		95 ± 34	74 ± 32
2 km		71 ± 26	58 ± 47		95 ± 35	69 ± 30
3 km		69 ± 19	56 ± 40		86 ± 34	82 ± 43
4 km		86 ± 33*[c]	47 ± 24*[c]		87 ± 23	74 ± 35
5 km		61 ± 25	56 ± 43		85 ± 28	77 ± 33
Mean	82 ± 11	73 ± 27	55 ± 37	75 ± 7	90 ± 29	76 ± 33

*[a]Denotes a significant difference between the BB and low breast support conditions.
*[b]Denotes a significant difference between the BB and high breast support conditions.
*[c]Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Significant main effect of breast support on the peak RMS pectoralis major muscle during the two minute ($F_{(2, 9)} = 3.662$, $p = .046$, $\eta = .289$, $1\text{-}\beta = .598$) and five kilometre ($F_{(1, 9)} = 7.506$, $p = .023$, $\eta = .445$, $1\text{-}\beta = .685$) treadmill running.

Table 2. Mean (SD) normalised (%) peak RMS and *i*EMG of the anterior deltoid during the two minute and five kilometre treadmill run trials, in three breast support conditions.

Intervals	RMS (%)			*i*EMG (%)		
	BB	LOW	HIGH	BB	LOW	HIGH
2 minutes	72 ± 16*[ab]	45 ± 26*[a]	53 ± 32*[b]	78 ± 13	74 ± 54†	65 ± 39†
1 km		45 ± 21	56 ± 25		77 ± 43	70 ± 35
2 km		34 ± 15	52 ± 32		72 ± 43	80 ± 44
3 km		40 ± 11	79 ± 32		86 ± 44	94 ± 34
4 km		45 ± 12	54 ± 23		83 ± 47†	102 ± 40†
5 km		52 ± 19	68 ± 39		90 ± 45	99 ± 42
Mean	72 ± 16	44 ± 18	60 ± 31	78 ± 13	80 ± 38	85 ± 40

*[a]Denotes a significant difference between the BB and low breast support conditions.
*[b]Denotes a significant difference between the BB and high breast support conditions.
*[c]Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Significant main effect of breast support on peak RMS anterior deltoid activity during the two minute running ($F_{(2, 9)} = .359$, $p = .031$, $\eta = .353$, $1\text{-}\beta = .669$). Significant main effect of intervals of run on the *i*EMG anterior deltoid activity during the five kilometre run ($F_{(5, 9)} = 4.018$, $p = .006$, $\eta = .365$, $1\text{-}\beta = .913$).

Table 3. Mean (SD) normalised (%) peak RMS and *i*EMG of the medial deltoid during the two minute and five kilometre treadmill run trials, in three breast support conditions.

Intervals	RMS (%)			*i*EMG (%)		
	BB	LOW	HIGH	BB	LOW	HIGH
2 minutes	83 ± 12*^{b}	70 ± 20*^{c}	54 ± 17*^{bc}	82 ± 8*^{b}	74 ± 27	62 ± 22*^{b}
1 km		77 ± 20*^{c}	55 ± 19*^{c}		79 ± 32	63 ± 25
2 km		83 ± 31*^{c}	63 ± 28*^{c}		86 ± 44	67 ± 27
3 km		71 ± 19	59 ± 24		79 ± 44	71 ± 29
4 km		69 ± 21	56 ± 20		76 ± 29	65 ± 24
5 km		61 ± 14	65 ± 28		71 ± 28	70 ± 29
Mean	83 ± 12	72 ± 21	59 ± 22	82 ± 8	78 ± 33	66 ± 25

*^{a}Denotes a significant difference between the BB and low breast support conditions.
*^{b}Denotes a significant difference between the BB and high breast support conditions.
*^{c}Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

N.B. Significant main effect of breast support on peak RMS medial deltoid activity during two minute ($F_{(2, 9)}$ = 9.327, p = .002, η = .509, 1-β = .953) and five kilometre ($F_{(1, 9)}$ = 7.101, p = .026, η = .441, 1-β = .661) treadmill running. Significant main effect of breast support on *i*EMG of the medial deltoid during two minute treadmill running ($F_{(2, 9)}$ = 4.832, p = .021, η = .349, 1-β = .726).

Table 4. Mean (SD) normalised (%) peak RMS and *i*EMG of the upper trapezius during the two minute and five kilometre treadmill run trials, in three breast support conditions.

Intervals	RMS (%)			*i*EMG (%)		
	BB	LOW	HIGH	BB	LOW	HIGH
2 minutes	81 ± 7	70 ± 19	77 ± 36	82 ± 9	78 ± 31	95 ± 60
1 km		75 ± 31	70 ± 34		70 ± 25	99 ± 53
2 km		67 ± 26	87 ± 36		66 ± 30	93 ± 36
3 km		69 ± 39	85 ± 36		70 ± 23	93 ± 37
4 km		71 ± 32	86 ± 47		73 ± 28	96 ± 38
5 km		78 ± 43	91 ± 46		79 ± 31	99 ± 40
Mean	81 ± 7	72 ± 32	83 ± 38	82 ± 9	73 ± 27	96 ± 43

*^{a}Denotes a significant difference between the BB and low breast support conditions.
*^{b}Denotes a significant difference between the BB and high breast support conditions.
*^{c}Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the kilometre intervals.

Table 5. Mode (SD) ratings of exercise-related breast pain during the first two minutes of running and the fifth kilometre interval, in three breast support conditions.

Breast support condition	**Run interval**	
	2 minutes	**5 km**
BB	9 ± 1	N/A
LOW	5 ± 1*[ac]	3 ± 1†
HIGH	0 ± 1*[bc]	0 ± 1

*[a]Denotes a significant difference between the BB and low breast support conditions.
*[b]Denotes a significant difference between the BB and high breast support conditions.
*[c]Denotes a significant difference between the low and high breast support conditions.
†Denotes a significant difference between the first two minutes and the fifth kilometre interval within a support.

Figure captions

Figure 1. Electrode placement on the (A) pectoralis major, (B) anterior deltoid, (C) medial deltoid, and the (D) upper trapezius muscles following the SENIAM guidelines.

Figures