Plantar pressure differences between cases with symptoms of chronic exertional compartment syndrome and asymptomatic controls

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Abstract

Background: Anterior chronic exertional compartment syndrome of the leg has been hypothesised to develop due to excessive muscle activity and foot pronation. Plantar pressure variables related to lower limb muscle activity and foot type may therefore provide insight into this condition.

Methods: 70 male cases and 70 asymptomatic controls participated. A clinical diagnosis was established from typical symptoms, with clinical examination excluding other pathologies. Plantar pressure variables during walking, hypothesised to be related to anterior compartment muscle activity or had shown predictive validity for general exercise-related lower leg pain, were extracted.

Findings: Cases were shorter in height (mean difference 2.4cm), had greater body mass (mean difference 4.4kg) and had reduced ankle dorsiflexion range of motion than controls (mean difference 1.5cm). Foot-type and toe extensor - related plantar pressure variables did not differ between groups (P>0.05). The magnitude of medial forefoot loading was the strongest plantar pressure predictor of the presence of chronic exertional compartment syndrome (Odds ratio:0.87, P=0.005). There was also some evidence of greater lateral heel loading at 5% of stance time (P=0.049-0.054).

Interpretation: The lack of association with foot type and toe extensor activity - related plantar pressure variables suggest that these are not risk factors for the development of chronic exertional compartment syndrome, contrary to earlier hypotheses. The greater lateral to medial loading could theoretically represent increased Tibialis anterior muscle activity at heel strike but a subsequent loss of control as the ankle is lowered. Future studies directly investigating muscle activity and function are now required.

Keywords: exercise-induced leg pain; chronic exertional compartment syndrome; biomechanics; plantar pressure; military training.

Introduction

Chronic exertional compartment syndrome (CECS) is an overuse condition presenting as pain in the lower limb. It has been described in numerous compartments of the body, although the anterior compartment of the lower leg is most commonly affected (Reneman, 1975). In up to 98% of cases the condition is bilateral (Reneman, 1975). While the condition is often described as an overuse injury; the mechanism of injury is unclear.

It has also recently been hypothesised to be the underlying cause of pain in CECS rather than a pathological increase in intramuscular compartment pressure (Franklyn-Miller et al., 2014, Roberts and Franklyn-Miller, 2012). However, a case-control study has since demonstrated higher resting standing pressures when anterior compartment muscle activity is minimal implying a structural aetiology (Roscoe, Roberts, & Hulse, 2015). Nevertheless, excessive anterior compartment muscle activity is still a likely candidate as a risk factor for the development of CECS. Despite this, the function of the anterior compartment musculature during gait has never been investigated in this population.

Plantar pressure measurement provides a method of investigating the impact of both muscle activity and anatomy on the forces applied to the foot. It has previously been demonstrated to be related to lower limb muscle activity (Ferris et al., 1995, Morag and Cavanagh, 1999) and foot type (Caravaggi, Giacomozzi, & Leardini, 2014, Cavanagh and Rodgers, 1987, Sánchez-Rodríguez et al., 2012). Foot type has also been observed to have an effect on Tibialis anterior muscle activity in several studies (Murley et al., 2009). Using plantar pressure, foot type has been directly characterised by the calculation of a dynamic arch index (Cavanagh and Rodgers, 1987). The impulse under all the metatarsals has also been demonstrated to have a strong correlation to medial longitudinal arch range of motion (Caravaggi, Giacomozzi, & Leardini, 2014) and arch height (Teyhen et al., 2009).

Activity of the toe extensor muscles may also be characterised by plantar pressure. Pressure underneath the toes has previously been demonstrated to be affected by simulated flexor hallucis longus and flexor digitorum longus activity (Ferris et al., 1995). It was assumed in our analysis that activity of the antagonists located in the anterior compartment (extensor hallucis longus and extensor digitorum longus) would have a similar effect (i.e. reduction of toe pressures).

A single study has investigated plantar pressure in 20 patients with CECS (Roscoe et al., 2016). They observed reductions in stance time and the time from initial foot contact to initial full forefoot contact that may be a result of alterations in anterior compartment activity/function. A greater understanding of ankle dorsiflexor and toe extensor activity in this condition is now needed.

This study therefore aimed to compare, in a case-control study, the plantar pressure variables described above that have previously been associated with anterior compartment muscle activity or had shown predictive validity for all-cause exercise-related lower leg pain (Willems et al., 2006). A secondary aim was to compare the variables investigated by Roscoe et al. (2016) in a larger cohort. We hypothesised that those variables associated with anterior compartment muscle activity and the development of all-cause exercise-related lower leg pain would be associated with CECS.

Materials and methods

70 male cases with symptoms consistent with CECS of the anterior compartment of the leg and 70 asymptomatic controls participated following informed consent. A consensus diagnosis of CECS was established from typical symptoms, with clinical examination excluding other pathologies. Controls were recruited from the British Armed forces. Cases were recruited from two military rehabilitation centres. Ethical approval was granted by the MOD Research Ethics Committee.

Cases required the following: symptoms of exercise-induced leg pain consistent with a diagnosis of anterior compartment CECS; no diagnosis other than CECS more likely; absence of multiple lower limb pathologies; and, no previous lower limb surgery. While intramuscular compartment pressure measurement is considered the gold standard for diagnosis (Roscoe, Roberts, & Hulse, 2015); clinical examination alone has been suggested to provide an accurate diagnosis for referral for surgery (Ali et al., 2013, Orlin, Oen, & Andersen, 2013, van den Brand et al., 2005). As pressure measurement was not available for this study, a clinical diagnosis was used. Controls were included when they had no history of musculoskeletal leg pain in the previous 12 months; and no current pain at any site, including during exercise activities.

Participants completed the Short Pain Inventory that measures both current physical pain and the emotional consequences of pain (Kilminster and Mould, 2002). Participant age, height (stadiometer; SECA, Birmingham, UK)) and body mass (medical grade scales; SECA, Birmingham, UK) were recorded. A weight-bearing dorsiflexion device (Jones et al., 2005) was used to measure the anterior-posterior distance between the knee and the hallux during a weight-bearing lunge; anatomical parameters that could influence this distance were therefore also recorded (UK shoe size/lower leg length (tibial tuberosity to lateral malleolus)).

Plantar pressure measurement and data extraction

Participants were asked to walk over a 2m x 0.4m x 0.02m pressure plate (RSScan International, Olen, Belgium) fitted flush to the floor of the laboratory; and were free to choose the order of foot placement. Participants completed a dynamic calibration and familiarisation traverses of the laboratory. Data was then collected at a natural, relaxed, self-selected walking velocity until a minimum of 3 valid foot contacts for both left and right feet had been captured at 125Hz (De Cock et al., 2006). Each foot was automatically divided into 10 zones (Hallux (T1), lesser toes, metatarsals 1-5 (M1,M2,M3,M4,M5), midfoot, medial/lateral heel (HM/HL)) by Footscan® (v7.97, RSScan International) software; these were used to calculate all loading-related variables. Data was extracted from Footscan® using the default exports. These data were then processed within Scilab (v5.3.2; INRIA, France) to generate mean values of each plantar pressure variable described below for left and right feet.

Primary variables

1. Arch index
2. Impulse under all the metatarsal zones
3. Medio-lateral centre of force (COF) position at last foot contact
4. Antero-posterior COF position at initial foot contact
5. Medio-lateral pressure ratio during forefoot contact phase (initial metatarsal contact to first instant all metatarsals make contact)
    a. [(HM+M1+M2)-(HL+M4+M5)]/(HM+HL+M1+M2+M3+M4+M5+T1)
6. Toe contact area at mid-stance
7. Peak force and impulse under the hallux
8. Peak force and impulse under the lesser toes

Secondary variables

1. Stance time
2. Foot progression angle
3. Mean medial-lateral displacement of COF during stance
4. Time from initial foot contact to initial full forefoot contact
5. Medial-lateral distribution of pressure under the heel at at initial foot contact, 5% of stance time and time of initial full forefoot contact
    a. HM/(HM+HL)
6. Mean ratio between 1^{st} and 5^{th} metatarsal loading during stance
    a. [(M1-M5)/((M1+M5)/2)]*100

Statistical analysis

Bootstrapped t-tests were carried out on all variables using the bias-corrected and accelerated method (Efron, 1987). Significant variables were then entered into a forward stepwise multinomial logistic regression model. The statistic (Likelihood ratio, Wald statistic, and conditional statistic) used in the test for variable inclusion did not affect the variables in the final model. Means and 95% CIs are reported unless otherwise stated. SPSS (v21; SPSS Inc, USA) was used for all analyses with alpha set to 0.05.

Results

Cases reported relatively low levels of pain (mean severity score 0.66) at rest although significantly more than controls (t=5.09, P=0.001). This was accompanied with reports of significantly greater sadness (mean difference=0.53, t=2.53, P=0.016) and anxiety (mean difference=0.49, t=2.21, P=0.028) than cases. Pain was not reported to be aggravated by cases or controls during testing demonstrating that sufficient rest was provided between each traverse.

Cases (28(5) years) were marginally younger than controls (32(6) years). Cases (1.759(6.8)m) were 2.4cm shorter than controls (1.783(7.3)m) although this was marginally higher than the accepted level of significance (P=0.051). Cases (85.8(12.3)kg) were 4.4kg heavier (P=0.026) than controls (81.4(10.4)kg). Weight-bearing dorsiflexion range of motion was significantly lower (95% CI of difference [-26.7,-3.5], *P*=0.012, Cohens d=0.4) in cases (113(40)mm) than controls (128(30)mm). There were no differences (*P*>0.3) in shoe size (cases 9.0(1.3) vs controls 9.2(1.4)) or lower leg length (cases 35.8(2.1)cm vs controls 36.2(2.5)cm).

The primary analysis did not find any significant differences for any of the plantar pressure variables (Table 1). The secondary analysis demonstrated significantly greater medial forefoot loading (*P*=0.019-0.020); and borderline significantly greater lateral heel loading at 5% of stance time (*P*=0.049-0.054) and greater overall medial COF (*P*=0.013-0.086) in cases. The results of the primary analysis suggest that the differences observed in the medial-lateral COF normalise by last foot contact. No other significant differences were observed (Table 2).

Table 1 Differences between cases and controls in the primary analysis. 95% CIs and p-values are bootstrapped. Degrees of freedom = 138 for all plantar pressure variables.

Variable	Mean difference (95% CI)	T-value	*P*-value
Weight-bearing dorsiflexion range of motion (mm)	-15.0 (-26.7,-3.5)	-2.52	0.012
Arch index	0.0015 (-0.0153,0.016)	0.184	0.835
Impulse: metatarsal zones (Ns)	6.71 (-15.3,27.8)	0.653	0.533
Medio-lateral centre of force position at last foot contact (mm)	-0.0069 (-0.0372,0.0264)	-0.413	0.682
Antero-posterior centre of force position at initial foot contact (mm)	-0.0012 (-0.0053,0.0035)	-0.488	0.645
Medio-lateral pressure ratio during forefoot contact phase	-0.0908 (-3.3108,2.9767)	-0.062	0.947
Toe contact area at midstance (as percentage of toe contact area during stance phase)	1.29 (-1.29,3.9)	0.964	0.346
Peak force: hallux zone (N)	11.8067 (-14.7578,38.7605)	0.851	0.418
Peak force: lesser toes (N)	-4.2064 (-12.1415,3.4802)	-1.056	0.297
Impulse: hallux zone (Ns)	3.99 (-0.74,8.94)	1.579	0.125
Impulse: lesser toes (Ns)	-0.67 (-2.13,0.58)	-0.984	0.345

Table 2 Differences between cases and controls in the secondary analysis. 95% CIs and p-values are bootstrapped. Degrees of freedom = 138 for all plantar pressure variables.

Variable	Mean difference (95% CI)	T-value	*P*-value
Stance time (ms)	0.08(-0.06,0.21)	1.17	0.27
Foot progression angle (°)	-0.63(-2.90,1.33)	-0.63	0.54

Mean medial-lateral displacement of COF during stance (mm)	0.74(-0.05,1.51)	1.85	0.09
Time from initial foot contact to initial full forefoot contact (IFFC; ms)	8.32(-6.24,23.2)	1.41	0.15
Medial-lateral heel pressure at initial foot contact	-0.02(-0.04,0.005)	-1.65	0.11
Medial-lateral heel pressure at 5% of stance time	-0.02(-0.04,0.0006)	-2.08	0.054
Medial-lateral heel pressure at time of IFFC	-0.01(-0.03,0.001)	-1.96	0.058
Overall medial-lateral forefoot loading	1.92(0.37,3.49)	2.50	0.02

Logistic regression demonstrated that height, mass and medial-lateral forefoot loading were the best predictors of group membership. No other variables added any further predictive value and were not entered into the logistic regression model (Table 3). The goodness-of-fit test indicated that the logistic regression model does not misrepresent the data (*P*=0.967).

Table 3 Logistic Regression Analysis Results[a]

Predictor[b]	Regression Coefficient (SE)	Wald Statistic	Odds Ratio	*P*-value
Height	0.150	14.4	1.16	<0.001
Mass	-0.105	18.3	0.900	<0.001
Overall medial-lateral forefoot loading	-0.136	7.82	0.873	0.005
Intercept[c]	-17.9	9.63	<0.001	0.002

[a]Pseudo R^2 = 0.223-0.298, [b]For each predictor, df=1, [c]The constant in the model representing the log odds when all predictors are 0

Discussion

In this study, we investigated whether anthropometry, ankle range of motion and plantar pressure variables differ between cases and controls. Our results show that cases appear to be shorter in height with a greater body mass and reduced ankle dorsiflexion range of motion. Cases and controls have similar arch indices and toe extensor activity - related plantar pressure variables; but do demonstrate differences in the medial-lateral distribution of pressure under the heel and forefoot.

The relatively low pain levels at rest observed are in agreement with the typical description of CECS as a type of exercise-induced leg pain (Willems et al., 2006). This study is the first to report mood disturbances in this group of patients. The greater sadness and anxiety are likely related to the potential career implications associated with CECS in the military and the mood disturbances typically induced and associated with pain (Kilminster, Power, & Fozardz, 2000).

The identification of small stature as a risk factor for the development of CECS supports previous findings for military patients (Roscoe, Roberts, & Hulse, 2015) strengthening the evidence for this measure. This larger study does however suggest that the effect size may be smaller than originally thought. Shorter stature may result in an increased stride length during marching that could cause an increased demand on Tibialis anterior and subsequent development of CECS (Roberts et al., 2016b).

Two military studies have also observed greater body mass in cases (Birtles et al., 2002, Roberts et al., 2016a). Small effect sizes that were not statistically significant have also been observed in two additional studies (Rorabeck et al., 1988, Varelas et al., 1993). It is unclear whether this is a result of deconditioning following the development of CECS or a risk factor for the condition itself.

Controls demonstrated similar ankle dorsiflexion range of motion values to those previously published (Bennell et al., 1998). Previous studies have reported that long distance runners have tighter plantarflexors and hamstrings than untrained individuals (Kubo et al., 2015, Wang et al., 1993). Similarly, tendon stiffness is increased by resistance training (Kubo, Kanehisa, & Fukunaga, 2002). A greater body mass index is also associated with decreased joint mobility (Soucie et al., 2011). Our finding may therefore be a reflection of greater usage of the plantarflexors in this population due to the greater body mass and reduced stature, necessitating a relatively longer stride (Roberts et al., 2016b), of cases. Alternatively this finding could be theorised to result in increased anterior compartment activity during swing phase due to the resistance of the flexors. Further research is required to confirm this.

Our results suggest that foot type is not a risk factor for the development of CECS. This is surprising given that Tibialis anterior muscle activity is modulated by foot type, and over-activity of this muscle is proposed to be key to the development of CECS (Tweed and Barnes, 2008). Our results may help explain the poor efficacy of conservative treatment such as the provision of foot orthoses (Fronek et al., 1987, Martens et al., 1984, Sebik and Dogan, 2008, Wiley et al., 1987). Direct measurement of foot type to confirm these findings is warranted in future studies in this population.

To the author's knowledge, no previous studies have quantified toe extension during gait in a healthy population. Our results suggest that some toe extension at mid-stance is a normal occurrence. This is evidenced by the observation that only 10% of all the sensors identified as being under the toes were active at mid-stance. Clinical observations of 'persistent toe extension at mid-stance' have previously been described in patients with CECS (Franklyn-Miller et al., 2014). However our findings do not suggest that there is over-activity of these muscles during stance.

Our observations are in contrast to the findings of Willems (2006). This emphasises the need to identify gait-related risk factors for individual conditions, injury locations and populations. The risk factors identified by Willems (2006) are therefore likely to be most predictive of the most common injury observed. Unfortunately the injury distribution was not reported for the Willems (2006) study; although the focus on medial tibial stress syndrome in the discussion suggests that CECS may not have been the primary diagnosis. We also used an automatic zoning method that resulted in larger zones than the semi-automatic identification method used by Willems (2006) that may explain some of the difference in results.

The secondary analysis found differences in variables that had not been identified in the earlier smaller study of plantar pressure in this population (Roscoe et al., 2016). Our results provide some evidence that patients with CECS walk with greater lateral pressure under the heel and stronger evidence that this is followed by greater medial pressure under the forefoot, although this is not associated with a more pronated dynamic arch index. It is suggested that these differences were not identified in the earlier study due to the lower sample size. The differences observed may be due to differences in Tibialis anterior activity and function. For example, a medial shift in heel loading at initial contact has been simulated when the force output of Tibialis anterior is reduced (Gefen, 2001). The greater lateral heel loading at the beginning of stance in cases may therefore be due to increased Tibialis anterior activity. The greater transfer of forces medially however may indicate that the subsequent control of ankle movement is impaired. Impairment of Tibialis anterior has previously been implied from the results of two earlier studies (Roberts et al., 2016b, Roscoe et al., 2016). However, direct observations of the activity and function of Tibialis anterior are required to confirm this hypothesis.

Our study design is limited in its ability to distinguish between cause and effect; the findings would therefore ideally be confirmed in a further longitudinal study. We are unable to rule out the possibility that the age differences observed could also reflect a longer exposure to military tasks such as marching that may have influenced the results. There is no evidence of age-related differences in plantar pressure variables and whereas range of motion is more likely to be reduced in the older group than the younger cohort found here (Vandervoort et al., 1992). Diagnosis of CECS was based on a clear clinical history rather than IMCP measurement due to strong evidence that IMCP testing had poor diagnostic validity at the start of this study (Roberts and Franklyn-Miller, 2012). Recently published data now demonstrates that the diagnosis can only be made accurately using IMCP when it is measured during exercise to the limits of pain tolerance (Roscoe, Roberts, & Hulse, 2015). Future studies would therefore ideally use this new diagnostic method for case selection.

In summary, this study demonstrates differences in anthropometry and joint mobility that provide further evidence that small stature may be a key risk factor for the development of CECS in this population. The lack of association with foot type and toe extensor activity - related plantar pressure variables suggest that these are not risk factors for the development of CECS, contrary to earlier hypotheses. The differences observed in the secondary analysis provide insights into the condition that should inform the direction of future studies.

References

Ali, T., Mohammed, F., Mencia, M., Maharaj, D., Hoford, R., 2013. Surgical management of exertional anterior compartment syndrome of the leg. West Indian Med. J. 62, 529-532.

Bennell, K.L., Talbot, R.C., Wajswelner, H., Techovanich, W., Kelly, D.H., Hall, A.J., 1998. Intra-rater and inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion. Aust. J. Physiother. 44, 175-180.

Birtles, D.B., Minden, D., Wickes, S.J., M Puxley, K.P., A Llewellyn, M.G., Casey, A., Rayson, M.P., Jones, D.A., Newham, D.J., 2002. Chronic exertional compartment syndrome: muscle changes with isometric exercise. Med. Sci. Sports Exerc. 34, 1900-1906.

Caravaggi, P., Giacomozzi, C., Leardini, A., 2014. Foot segments mobility and plantar pressure in the normal foot. Journal of Foot and Ankle Research. 7, 1-2.

Cavanagh, P.R., Rodgers, M.M., 1987. The arch index: a useful measure from footprints. J. Biomech. 20, 547-551.

De Cock, A., Willems, T., Witvrouw, E., Vanrenterghem, J., De Clercq, D., 2006. A functional foot type classification with cluster analysis based on plantar pressure distribution during jogging. Gait Posture. 23, 339-347.

Efron, B., 1987. Better bootstrap confidence intervals. Journal of the American statistical Association. 82, 171-185.

Ferris, L., Sharkey, N.A., Smith, T.S., Matthews, D.K., 1995. Influence of extrinsic plantar flexors on forefoot loading during heel rise. Foot Ankle Int. 16, 464-473.

Franklyn-Miller, A., Roberts, A., Hulse, D., Foster, J., 2014. Biomechanical overload syndrome: defining a new diagnosis. Br. J. Sports Med. 48, 415-416.

Fronek, J., Mubarak, S.J., Hargens, A.R., Lee, Y.F., Gershuni, D.H., Garfin, S.R., Akeson, W.H., 1987. Management of chronic exertional anterior compartment syndrome of the lower extremity. Clin. Orthop. Relat. Res. (220), 217-227.

Gefen, A., 2001. Simulations of foot stability during gait characteristic of ankle dorsiflexor weakness in the elderly. IEEE Trans. Neural Syst. Rehabil. Eng. 9, 333-337.

Hunt, A.E., Smith, R.M., 2004. Mechanics and control of the flat versus normal foot during the stance phase of walking. Clin. Biomech. 19, 391-397.

Jones, R., Carter, J., Moore, P., Wills, A., 2005. A study to determine the reliability of an ankle dorsiflexion weight-bearing device. Physiotherapy; Physiotherapy. 91, 242-249.

Kilminster, S.G., Mould, G.P., 2002. Comparison of internal reliability and validity of the McGill Pain Questionnaire and the Short Pain Inventory. International journal of pharmaceutical medicine. 16, 87-95.

Kilminster, S.G., Power, M.W., Fozardz, J.R., 2000. Survey of pain in two medical and dental clinics with non-patient controls using the Short Pain Inventory©. International journal of pharmaceutical medicine. 14, 137-147.

Kubo, K., Kanehisa, H., Fukunaga, T., 2002. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. J. Physiol. 538, 219-226.

Kubo, K., Miyazaki, D., Yamada, K., Yata, H., Shimoju, S., Tsunoda, N., 2015. Passive and active muscle stiffness in plantar flexors of long distance runners. J. Biomech. 48, 1937-1943.

Langevin, H.M., Stevens-Tuttle, D., Fox, J.R., Badger, G.J., Bouffard, N.A., Krag, M.H., Wu, J., Henry, S.M., 2009. Ultrasound evidence of altered lumbar connective tissue structure in human subjects with chronic low back pain. BMC Musculoskelet. Disord. 10, 151-2474-10-151.

Martens, M.A., Backaert, M., Vermaut, G., Mulier, J.C., 1984. Chronic leg pain in athletes due to a recurrent compartment syndrome. Am. J. Sports Med. 12, 148-151.

Morag, E., Cavanagh, P.R., 1999. Structural and functional predictors of regional peak pressures under the foot during walking. J. Biomech. 32, 359-370.

Murley, G.S., Landorf, K.B., Menz, H.B., Bird, A.R., 2009. Effect of foot posture, foot orthoses and footwear on lower limb muscle activity during walking and running: a systematic review. Gait Posture. 29, 172-187.

Murley, G.S., Menz, H.B., Landorf, K.B., 2009. Foot posture influences the electromyographic activity of selected lower limb muscles during gait. J. Foot Ankle Res. 2, 35-1146-2-35.

Orlin, J.R., Oen, J., Andersen, J.R., 2013. Changes in leg pain after bilateral fasciotomy to treat chronic compartment syndrome: a case series study. J. Orthop. Surg. Res. 8, 6-799X-8-6.

Reneman, R.S., 1975. The anterior and the lateral compartmental syndrome of the leg due to intensive use of muscles. Clin. Orthop. Relat. Res. (113), 69-80.

Roberts, A., Franklyn-Miller, A., 2012. The validity of the diagnostic criteria used in chronic exertional compartment syndrome: A systematic review. Scand. J. Med. Sci. Sports. 22, 585-595.

Roberts, A., Roscoe, D., Hulse, D., Bennett, A., Dixon, S., 2016a. Biomechanical differences between cases with CECS and asymptomatic controls during running. British Journal of Sports Medicine. 50, e4-e4.

Roberts, A., Roscoe, D., Hulse, D., Bennett, A., Dixon, S., 2016b. Biomechanical differences between cases with CECS and asymptomatic controls during walking and marching. British Journal of Sports Medicine. 50, e4-e4.

Rorabeck, C.H., Bourne, R.B., Fowler, P.J., Finlay, J.B., Nott, L., 1988. The role of tissue pressure measurement in diagnosing chronic anterior compartment syndrome. Am. J. Sports Med. 16, 143-146.

Roscoe, D., Roberts, A., Hulse, D., Hughes, M., Shaheen, A., Bennett, A., 2016. Barefoot plantar pressure measurement in chronic exertional compartment syndrome. British Journal of Sports Medicine. 50, e4-e4.

Roscoe, D., Roberts, A.J., Hulse, D., 2015. Intramuscular compartment pressure measurement in chronic exertional compartment syndrome: new and improved diagnostic criteria. Am. J. Sports Med. 43, 392-398.

Sánchez-Rodríguez, R., Martínez-Nova, A., Escamilla-Martínez, E., Pedrera-Zamorano, J.D., 2012. Can the Foot Posture Index or their individual criteria predict dynamic plantar pressures? Gait Posture. 36, 591-595.

Sebik, A., Dogan, A., 2008. A technique for arthroscopic fasciotomy for the chronic exertional tibialis anterior compartment syndrome. Knee Surg. Sports Traumatol. Arthrosc. 16, 531-534.

Soucie, J.M., Wang, C., Forsyth, A., Funk, S., Denny, M., Roach, K.E., Boone, D., Hemophilia Treatment Center Network, 2011. Range of motion measurements: reference values and a database for comparison studies. Haemophilia. 17, 500-507.

Stecco, C., Cappellari, A., Macchi, V., Porzionato, A., Morra, A., Berizzi, A., De Caro, R., 2014a. The paratendineous tissues: an anatomical study of their role in the pathogenesis of tendinopathy. Surg. Radiol. Anat. 36, 561-572.

Stecco, C., Pavan, P., Pachera, P., De Caro, R., Natali, A., 2014b. Investigation of the mechanical properties of the human crural fascia and their possible clinical implications. Surg. Radiol. Anat. 36, 25-32.

Teyhen, D.S., Stoltenberg, B.E., Collinsworth, K.M., Giesel, C.L., Williams, D.G., Kardouni, C.H., Molloy, J.M., Goffar, S.L., Christie, D.S., McPoil, T., 2009. Dynamic plantar pressure parameters associated with static arch height index during gait. Clin. Biomech. (Bristol, Avon). 24, 391-396.

Tweed, J.L., Barnes, M.R., 2008. Is eccentric muscle contraction a significant factor in the development of chronic anterior compartment syndrome? A review of the literature. Foot (Edinb). 18, 165-170.

van den Brand, J.G., Nelson, T., Verleisdonk, E.J., van der Werken, C., 2005. The diagnostic value of intracompartmental pressure measurement, magnetic resonance imaging, and near-infrared spectroscopy in chronic exertional compartment syndrome: a prospective study in 50 patients. Am. J. Sports Med. 33, 699-704.

Vandervoort, A.A., Chesworth, B.M., Cunningham, D.A., Paterson, D.H., Rechnitzer, P.A., Koval, J.J., 1992. Age and sex effects on mobility of the human ankle. J. Gerontol. 47, M17-21.

Varelas, F.L., Wessel, J., Clement, D.B., Doyle, D.L., Wiley, J.P., 1993. Muscle function in chronic compartment syndrome of the leg. J. Orthop. Sports Phys. Ther. 18, 586-589.

Wang, S.S., Whitney, S.L., Burdett, R.G., Janosky, J.E., 1993. Lower extremity muscular flexibility in long distance runners. J. Orthop. Sports Phys. Ther. 17, 102-107.

Wiley, J., Clement, D., Doyle, D., Taunton, J., 1987. A primary care perspective of chronic compartment syndrome of the leg. Physician Sportsmed. 15, 110-&.

Willems, T.M., De Clercq, D., Delbaere, K., Vanderstraeten, G., De Cock, A., Witvrouw, E., 2006. A prospective study of gait related risk factors for exercise-related lower leg pain. Gait Posture. 23, 91-98.