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Assessment of lower leg muscle force distribution during isometric ankle dorsi and plantar flexion in patients with diabetes: a preliminary study

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ABSTRACT

Aim: The aim of this study was to evaluate the differences in ankle muscle strength using hand-held dynamometry and to assess difference in the isometric muscle force distribution between the people with diabetes and control participants.
Methods: The maximal muscle strength of ankle plantarflexion, dorsiflexion, eversion, inversion, lesser toes flexors and extensors, hallux flexors, and extensors was assessed in 20 people with diabetes and 20 healthy participants using hand-held dynamometry. The maximal isometric ankle plantarflexion and dorsiflexion were imported to OpenSim software to calculate 12 individual muscle (8 plantarflexors and 4 dorsiflexors) forces acting on ankle joint.
Results: A significant reduction in ankle strength for all measured actions and a significant decrease in muscle force for each of the 12 muscles during dorsi and plantar flexion were observed. Furthermore, the ratios of agonist to antagonist muscle force for 6 of the muscles were significantly different between the control group and the group with diabetes.
Conclusions: It is likely that the muscles for which the agonist/antagonist muscle force ratio was significantly different for the healthy people and the people with diabetes could be more affected by diabetes.

1. Introduction

Type 2 diabetes (DM2) is accompanied by a wide range of impairments. Previous investigations have shown that DM2 is associated with a loss of mobility (Lalli et al., 2013; Orr, Tsang, Lam, Comino, & Singh, 2006) and reduced muscle strength (Andreassen, Jakobsen, & Andersen, 2006). Several studies have also described impairment of gait (Brach, Talkowski, Strotmeyer, & Newman, 2008; Raspovic, 2013), foot ulceration (Raspovic, 2013) and increased risk of falling (Lalli et al., 2013) in neuropathic diabetic patients. Furthermore, a reduced walking speed, along with a compromised static and dynamic balance, have also been observed in older diabetic patients with neuropathy (Lalli et al., 2013). In addition, Andersen, Gjerstad, and Jakobsen (2004) and Andersen, Nielsen, Mogensen, and Jakobsen (2004) showed that DM2 is associated with loss of muscle strength around the ankle and knee joint, and Mueller, Minor, Sahrmann, Schaaf, and Strube (1994) revealed that diabetic neuropathic patients were unable to generate sufficient ankle joint moment, with a consequent reduction in the dynamic function during walking, resulting in a smaller step length and stride, reducing gait speed and cadence.

While neuropathy has been associated with impaired mobility, loss of muscle strength and decreased health-related quality of life, as reviewed elsewhere (Van Schie, 2008), several factors could be responsible for this limited mobility and decreased muscle strength in diabetic patients; such as intrinsic abnormalities in diabetic muscle, impaired capillary recruitment, peripheral arterial disease and diabetic polyneuropathy (Andersen, Gjerstad, et al., 2004; Andersen, Nielsen, et al., 2004; Lalli et al., 2013, Van Schie, 2008).

Although, most in vivo studies have analyzed muscle performance under isokinetic conditions (both active (Hatef, Bahrpeyma, & Tehrani, 2014) and passive (Hajrasouliha, Tavakoli, Esteki, & Nafisi, 2005)), a simple, widely used and objective tool in a clinic for measuring muscle strength is hand-held dynamometer (Abizanda et al., 2012). Hand-held dynamometers have been shown to be reliable for testing a number of muscle groups including those of the ankle (Burns, Redmond, Ouvrier, & Crosbie, 2005; Wang, Olson, & Protas, 2002), but this device does not give any information about the

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individual muscle forces distribution. Since muscle forces cannot be measured invasively (Pandy, 2001), these quantities are determined using indirect methods combining kinematic and kinetics analysis.

Muscle force distribution problem within biomechanics deals with the determination of the internal forces acting on the musculoskeletal system using the known resultant inter-segmental forces and moments. The force distribution across human joints is typically represented with an indeterminate set of system equations; this means that there are more unknowns than the number of equations that are most often used for calculating the muscle, ligament, and bone forces acting in and around joints. The analysis of muscle forces distribution is currently one of the major issues raised in biomechanics, requiring the use of sophisticated optimization models (Delp et al., 2007).

There has been a paucity of studies that investigate the individual muscle force distributions in people with diabetes. In light of the lack of such data, the aim of this pilot study was to evaluate differences in foot and ankle isometric muscle strength and to assess the difference in individual muscle force distributions between the people with diabetes and healthy controls.

2. Materials and methods

2.1. Participant recruitment and preparation

Forty-eight people with diabetes and severe neuropathy with a mean age of 59 ± 8.02 years, height of 1.66 ± 0.1 m and weight of 74.8 ± 7.23 kg participated in the study. Following a statistical analysis (detailed Section 2.4.1) a subset of 20 of the 48 diabetic patients with mean age of 59 ± 9.84 years, height of 1.63 ± 0.1 m, weight of 71.6 ± 12.1 kg and average duration of diabetes 14 ± 7.8 years were selected for analysis. The diagnostic criteria for composing the groups with signs and symptoms of neuropathy were based on the measurement of VPT at the Hallux, first, third or fifth metatarsals. The voltage was slowly increased at the rate of 1 V/sec and the VPT value was defined as the voltage level that produced a vibration that was sensed by the subject. The mean of the four records was calculated and neuropathy was diagnosed if the average was more than 25 V (Young, Breddy, Veves, & Boulton, 1994). Twenty healthy volunteers with mean age of 60.7 ± 7.5 years, height of 1.64 ± 0.6 m and weight of 73.2 ± 6.12 kg were screened and included in the study. In both groups, the numbers of men and women were the same—10 in each. A t-test was performed and showed no significant age differences between the healthy and diabetic group. The ethical approval was sought and granted by the local research ethics committee and all volunteers provided full informed consent.

2.2. Instrumentation and data collection

Isometric muscle strength was measured using a Citec hand-held dynamometer (CIT Technics, Haren, the Netherlands). The manufacturer's data state that the device was factory calibrated to a sensitivity of 0.1% and a range of 0–500 N. The hand-held dynamometer (HHD) measures the peak force produced by a muscle as it contracts while pushing against an object. A recent systematic review of HHD for assessment of muscle strength in the clinical setting found the instrument to be a reliable and valid tool (Stark, Walker, Phillips, Fejer, & Beck, 2011). Isometric muscle strength was assessed using the 'make test', whereby the examiner held the HHD stationary while the participants actively exerted a maximal force. All tests were performed with the participants in a supine position with hips and knees extended and the lower limb stabilized proximal to the ankle joint as directed by (CIT Technics, Haren, the Netherlands). The HHD was positioned against the lateral border of the foot distal to the base of the 5th metatarsal head to measure eversion; to the medial border of the foot, near the base of the 1st metatarsal head to measure inversion; against the metatarsal heads on the plantar surface of the foot to measure plantarflexion, and on the dorsal aspect of the foot proximal to the metatarsal heads to measure dorsiflexion and over the interphalangeal joint of the hallux for hallux plantarflexion and dorsiflexion. For testing of the lesser digits, the dynamometer was placed on the plantar surface of the digits. Moreover, for testing both the hallux and lesser toe strength, the ankle was passively placed in maximum plantar flexion to prevent co-contraction of the ankle plantar flexor muscles influencing the result.

Each participant performed submaximal test movements for familiarization prior to testing. Testing of each muscle group required a contraction of 3–5 seconds. Three repetitions were obtained for each muscle group, for each leg with a minimum rest period of 10 seconds between each contraction. The average of the three contractions was used for analysis as mean values have been shown to be more reliable than maximal values (Van den Beld, Van der Sanden, Sengers, Verbeek, & Gabreels, 2006). Verbal encouragement was given during each contraction. To assess repeatability of measurements, coefficients of variation (CVs) were calculated, which expresses between-trial variability as a percentage. It was suggested that CV values of 0.60 and greater indicate poor repeatability, 0.4–0.60 fair repeatability, 0.20–0.40 good repeatability and 0.20 and less excellent repeatability (Krysicki, Bartos, Dyczka, Królikowska, & Wasilewski, 2006). All values measured with HHD achieved good and excellent repeatability.

2.3. Musculoskeletal model

A generic musculoskeletal model with 19 degrees-of-freedom and 92 musculo-tendon actuators was used to generate the simulation in OpenSim 2.4 (Stanford, USA) (Delp et al., 2007). The model was dimensioned to represent a subject with a body mass of 72.6 kg. The feet of each subject were scaled to match the anthropometry, which was measured before the experiment. An inverse kinematics problem was solved to calculate the joint angles of the musculoskeletal model that best reproduce the experimental kinematics of the subject that was distributed with OpenSim software. Following this step, individual muscle forces were computed using the computed muscle control (CMC) tool. CMC is an optimization based control technique designed specifically for controlling dynamic models that are actuated by redundant sets of actuators whose force generating properties may be nonlinear and governed by differential equations. The purpose of (CMC) is to compute a set of muscle excitations that will drive a dynamic musculoskeletal model to track a set of desired kinematics in the presence of applied external forces (Thelen & Anderson, 2006). The OpenSim force data file was modified to allow simulations. For each subject plantarflexion force measured with HHD was put as a vertical force applied to toes as a body force and for each subject dorsiflexion force measured with HHD was applied as a vertical force with the same line as plantarflexion force but opposite direction also applied to toes as a body force. While the anterio-posterior and medio-lateral components of the ground reaction force are important during gait, in an isometric contraction we made sure that the measuring head of the dynamometer was held perpendicular to the plantar surface (in plantarflexion) and to the dorsal surface (in dorsiflexion). In this condition only the vertical component of the force causes a moment around the centre of rotation of the joint. Since the lever arm was perpendicular to the line of action of the force, the measured force by the dynamometer was the only component that exists during isometric dorsi and plantar flexion. For each person from the control and diabetic groups, muscle force distribution for each of the 12 muscles (8 ankle plantarflexors: flexor digitorum, flexor hallucis, gastrocnemius lateral head, gastrocnemius medial head, peronus brevis, peronuslongus, soleus, tibialis posterior and 4 ankle dorsiflexors: extensor digitorum, extensor hallucis, peroneus tertius, tibialis anterior) acting on the ankle joint was calculated.

2.4. Statistical analysis

2.4.1. Outliers and extremes

In order to achieve equinumerosity of the analysis groups (20 persons in each group) and in order to further simulation of muscle force distribution in the OpenSim software, the number of participants in the diabetes group was reduced. To do this the Statistica 8.0 software (StatSoft, PL) was used and analysis of outliers and extremes was applied. Analysis of outliers and extremes was applied for the following parameters: foot dorsiflexors, foot plantarflexors, foot inversion, foot eversion, lesser toes flexors, lesser toes extensors, hallux flexors, and hallux extensors which were measured using HHD device. Extreme values are the lowest and highest values in a given data set, while outliers are values that are significantly higher or lower than the remainder of the data. In order to be an outlier, the value must be:

- larger than quartile 3 by at least 1.5 times the interquartile range, or
- smaller than quartile 1 by at least 1.5 times the interquartile range (Aggarwal, 2013).

All participants with extreme values at both ends were excluded from further analysis.

2.4.2. Differences between groups

The ratio of agonist to antagonist (Ago/Ant) for each individual muscle was calculated in order to eliminate the fact that healthy persons applied more dorsiflexion and plantarflexion force using following formula:

$$\begin{aligned}\text{Ago/Ant} &= \frac{F_{\text{individual plantarflexion muscle for PF}_{\text{action}}}}{F_{\text{individual plantarflexion muscle for DF}_{\text{action}}}}\\ \text{or}\\ \text{Ago/Ant} &= \frac{F_{\text{individual dorsiflexion muscle for DF}_{\text{action}}}}{F_{\text{individual dorsiflexion muscle for PF}_{\text{action}}}}\end{aligned} \quad (1)$$

In order to assess the groups of dorsiflexion and plantarflexion muscles as a sum of individual muscle force contribution under applied plantarflexion and dorsiflexion measured force for both participants group the following ratios were applied:

$$\text{RPF} = \frac{\sum_{n=1}^{8} F_{\text{PF}_n} \text{ for PF}_{\text{action}}}{\sum_{n=1}^{8} F_{\text{PF}_n} \text{ for DF}_{\text{action}}} \qquad \text{RDF} = \frac{\sum_{n=1}^{4} F_{\text{DF}_n} \text{ for DF}_{\text{action}}}{\sum_{n=1}^{4} F_{\text{DF}_n} \text{ for PF}_{\text{action}}} \quad (2)$$

where: $\sum_{n=1}^{8} F_{\text{PF}_n} \text{ for PF}_{\text{action}}$ represents the sum of forces of the eight individual plantarflexors when measured by HHD plantarflexion force was applied during simulation. The same explanation applies to the other components of the formula (1).

Normality of measured, simulated and calculated data distribution was assessed using the Shapiro–Wilk test. Non parametric U Mann–Whitney test was used to determine statistical significance between the diabetic and control groups for all parameters. All data were analyzed using Statistica 8.0 with the alpha level set at 0.05.

3. Results

3.1. Outliers and extremes

An outlier and extreme are observations that lies an abnormal distance from other values in a random sample from a population. For all collected data for the diabetic group the box-and-whisker plots were completed in order to determine outliers and extremes points (Fig. 1).

Through further analysis, people with more than two extremes were eliminated, which could be any combination of experimentally measured values. In the plantarflexion group values which were less than 90 N and more than 190 N were considered extremes. For the dorsiflexors group extreme values were below 70 N and more than 170 N. For inversion and lesser toes extensors group extreme values were below 50 N and more than 110 N. Similar condition was found for foot eversion and lesser toes flexors 60 N and 120 N. Extremes values for hallux flexors were 60 N and 130 N, and for hallux extensors 40 N and 90 N.

3.2. Healthy and diabetes comparison

The Shapiro–Wilk test indicated that the measured and simulated data were not normally distributed ($P < 0.05$). Thus, in order to determine statistical significance between the diabetic and control groups for all parameters U Mann–Whitney test was used.

Results presented in Table 1 demonstrated a significant difference between the diabetic and control groups for all of measured parameters. Moreover, all measured parameter values in the healthy control group were almost 1.5 times higher than those in the diabetic group.

Results of simulation of individual muscle force distribution for plantarflexion and dorsiflexion acting force are presented in Table 2. Similar to the results from the HHD testing we observed significant differences between the diabetic and control groups for all of the individual muscle forces. Mean force for all muscles is almost 1.19 times higher for the control group during isometric plantarflexion and 1.11 during isometric dorsiflexion, when compared to the diabetic group.

By calculating the ratio of agonist to antagonist muscles using formula (1), the effect of the fact that the healthy controls applied more force than the patients with diabetes (as measured by the HHD) was eliminated. For Ago/Ant radio we found that half of the dorsiflexors (extensor digitorum, tibialis anterior) and half of the plantarflexors muscle (flexor digitorum, flexor hallucis, peronus longus, tibialis posterior) show no statistically significant difference ($P > 0.05$) between the groups of healthy subjects and patients.

Formula (2) was applied in order to assess the groups of dorsiflexion and plantarflexion muscles as a sum of individual muscle force contribution under applied plantarflexion and dorsiflexion measured force for both participants groups. Fig. 2 is a box-and-whisker plot showing the median and interquartile ranges of ratios for control and diabetic groups. Significant differences were found between the ratio calculated for control group during application of plantarflexion force and all other ratios for the control and diabetic groups ($P = 0.00$). Moreover, a significant difference was found between the ratio calculated for the

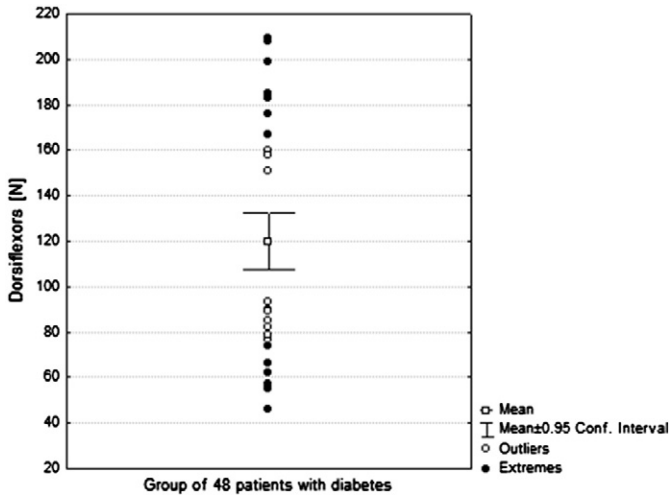

Fig. 1. Example of outliers and extremes for dorsiflexors data collected in group of 48 diabetic patients.

Table 1
The mean and standard deviation (SD) for muscle strength testing measured with HHD, for the diabetic and control groups.

Movement	Diabetic group mean (SD)	Control group mean (SD)	*P*-value
Plantarflexion [*N*]	142.2 (27.87)	203.68 (32.7)	0.000*
Dorsiflexion [*N*]	112.83 (24.75)	178.73 (27.41)	0.000*
Inversion [*N*]	77.7 (16.42)	114.7 (26.69)	0.000*
Eversion [*N*]	83.98 (13.15)	123.83 (25.88)	0.000*
Lesser toes flexors [*N*]	90.08 (17.24)	128.65 (33.05)	0.000*
Lesser toes extensors [*N*]	71.65 (13.1)	105.83 (27.8)	0.000*
Hallux flexors [*N*]	97.1 (19.93)	140.65 (34.68)	0.000*
Hallux extensors [*N*]	63.38 (10.6)	88.38 (28.54)	0.001*

* Significance at the $P < 0.05$ level for U Mann–Whitney test.

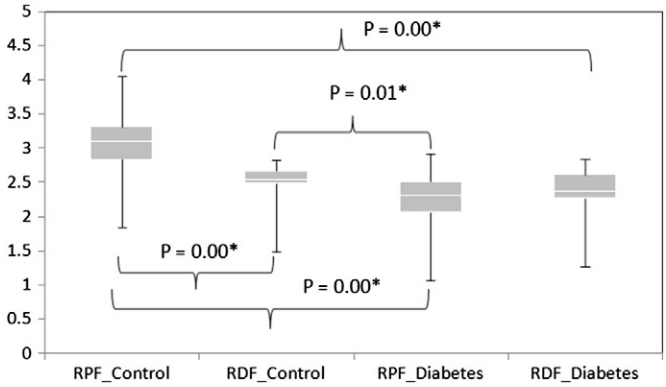

Fig. 2. Box and whisker plots (median and interquartile range) for ratios (RDF and RPF) for control and diabetic group, where RDF, RPF is the ratio of sum of agonist to sum of antagonist.

control group during application of dorsiflexion force and the diabetic group during application of plantarflexion force ($P = 0.01$).

4. Discussion

The aim of this study was to evaluate differences in foot and ankle muscle strength between patients with diabetes and control participants using hand-held dynamometry. The subsequent aim focused on the assessment of differences in individual muscle force distribution between the groups based on data from hand-held dynamometry. This study has shown a significant reduction in plantarflexion, dorsiflexion, inversion and eversion, lesser toes flexors, lesser toes extensors, hallux flexors and hallux extensors muscle strength in patients with diabetes. Consequently it was also found that individual muscle force for each of the 12 muscles (8 ankle plantarflexors and 4 ankle dorsiflexors) acting on the ankle joint was significantly less in diabetic group in comparison to the control group.

Duration of diabetes and poor metabolic control are well-known risk factors for the development of muscle weakness (Andersen, Gjerstad, et al., 2004; Andersen, Nielsen, et al., 2004; Harbo, Brincks, & Andersen, 2012). Weakness evaluated by manual testing has been reported to be an independent risk factor for the development of foot ulcers, probably because muscle weakness at the ankle and knee in diabetic neuropathy leads to abnormal application of pressure at the sole of the foot during walking (Andersen, Poulsen, Mogensen, & Jakobsen, 1996). The results of this study are in line with Park et al. (2006) who reported that muscle quality in both upper and lower extremities, defined as muscle strength per unit regional muscle mass, was significantly lower in men and women with diabetes than those without diabetes. Andreassen et al. (2006) observed a certain worsening in muscle performance in patients with peripheral neuropathy. Ijzerman et al. (2012) examined patients with and without polyneuropathy. In both group patients leg muscle strength was reduced by 30%–50% compared to healthy subject. We found a lower reduction in muscle strength measured by HHD in our patients (28%–37%) compared to healthy. Giacomozzi, D'Ambrogi, Cesinaro, Macellari, and Uccioli (2008) reported a significant reduction of ankle mobility. They showed that dorsal-flexing torque was significantly reduced in all patients and in all foot positions, the highest reduction was 28% for diabetic patients without neuropathy and 37% for patients withneuropathy. Since the torque depends on both the force and the distance from the axis of rotation, and considering that for isometric conditions this distance has a constant value, we can see that our results show a 37% reduction for dorsiflexors and a 30% reduction for plantarflexors. In summary, results presented in Table 1 demonstrate that all values measured by hand-held dynamometry including: plantarflexion, dorsiflexion, inversion and eversion, lesser toes flexors, lesser toes extensors, hallux flexors and hallux extensors in the healthy control group were almost 1.5 times higher than in the diabetic group.

Actual estimates of muscle forces can only be obtained with computational models in which the skeleton and muscles are both represented. Implemented in a variety of forms, musculoskeletal models have been used in conjunction with non-invasive measurements to obtain individual muscle forces during a number of movement tasks. Until now, simulation of muscle force distribution was applied for measured kinematics and kinetics parameters during gait for healthy and disabled persons (Anderson & Pandy, 1999;

Table 2
The mean and standard deviation (SD) for individual muscle force distribution for measured PF and DF action force and ratio of agonist to antagonist (Ago/Ant) for diabetic and control groups.

Individual muscle force	Diabetic group mean (SD)			Control group mean (SD)			*P*-value		
	PF action	DF action	Ago/Ant	PF action	DF action	Ago/Ant	PF action diabetic vs. control	DF action diabetic vs. control	Ago/Ant diabetic vs. control
Gastrocnemius medial head [*N*]	359.88 (55.16)	48.52 (0.15)	7.42 (1.18)	458.15 (44.55)	48.28 (0.09)	9.49 (0.94)	0.000*	0.000*	0.000*
Gastrocnemius lateral head [*N*]	64.71 (10.98)	23.29 (3.51)	2.84 (0.6)	84.34 (8.9)	22.4 (0.04)	3.77 (0.4)	0.000*	0.000*	0.000*
Soleus [*N*]	146.09 (40.07)	94.23 (0.61)	1.55 (0.44)	266.94 (75.31)	93.45 (0.29)	2.86 (0.81)	0.000*	0.000*	0.000*
Tibialis posterior [*N*]	79.39 (0.09)	78.88 (0.09)	1.01 (0)	79.53 (0.06)	78.77 (0.04)	1.01 (0)	0.000*	0.000*	0.279
Flexor digitorum [*N*]	9.29 (0.01)	9.24 (0.01)	1.01 (0)	9.31 (0.01)	9.23 (0.00)	1.01 (0)	0.000*	0.000*	0.417
Flexor hallucis [*N*]	9.23 (0.01)	9.14 (0.01)	1.01 (0)	9.25 (0.01)	9.13 (0.01)	1.01 (0)	0.000*	0.000*	0.297
Tibialis anterior [*N*]	172.17 (22.46)	421.71 (56.3)	2.46 (0.21)	223.84 (27.75)	569.32 (60.1)	2.55 (0.19)	0.000*	0.000*	0.085
Peronus brevis [*N*]	15.56 (0.01)	15.49 (0.01)	1.01 (0.01)	15.58 (0.01)	15.47 (0.01)	1.01 (0)	0.000*	0.000*	0.030*
Peronus longus [*N*]	35.91 (0.03)	35.74 (0.03)	1.01 (0.01)	35.95 (0.02)	35.7 (0.01)	1.01 (0)	0.000*	0.000*	0.058
Peroneus tertius [*N*]	6.58 (0.03)	10.83 (1.7)	1.65 (0.26)	6.55 (0.13)	14.91 (1.68)	2.28 (0.26)	0.000*	0.000*	0.000*
Extensor digitorum [*N*]	52.34 (6.95)	126.74 (15.91)	2.44 (0.32)	68.65 (8.81)	170.8 (21.04)	2.5 (0.23)	0.000*	0.000*	0.180
Extensor hallucis [*N*]	5.38 (0.47)	13.3 (1.68)	2.47 (0.27)	6.78 (0.86)	17.84 (2.08)	2.64 (0.22)	0.000*	0.000*	0.025*

* Significance at the $P < 0.05$ level for U Mann–Whitney test.

Wang & Gutierrez-Farewik, 2014). Within the current article, based on the data from a simple device which is the hand-held dynamometer, individual muscle force could be estimated. Results for the simulation of individual muscle force distribution for plantarflexion and dorsiflexion acting force (Table 2) show a significant decrease in muscle force for each of the 12 muscles. Mean force for all muscle is almost 16% lower for the diabetes group during isometric plantarflexion action and 10% lower during isometric dorsiflexion action. We need to note that the current study examined the muscle force contribution of diabetic neuropathic patients; hence the observed difference between the groups is attributed to the combined effect of neuropathy and diabetes. Giacomozzi et al. (2008), when examining groups of diabetic and diabetic neuropathic patients against healthy participants, attributed the overall decrease in the ankle moment to muscle atrophy as a result of muscle tissue glycation and damage as a result of impaired nerve conduction. These differences together with alterations of cartilages, ligaments and tendons as a result of glycation (Giacomozzi, D'Ambrogi, Uccioli, & Macellari, 2005; Wrobel & Najafi, 2010) could explain the deterioration in the muscle force contribution during isometric plantar and dorsi flexion contractions. Although the dynamometer is traditionally used for quantifying the agonists' moment generating capacity, co-activation of antagonists can complicate the interpretation of results essential for evaluating the effectiveness of a structured rehabilitation program. Co-activation of the antagonist during a contraction of the agonists results in a negative moment in relation to the moment developed by agonists, reducing the net resultant moment output. Very few studies have reported antagonistic co-activation during agonistic maximal isometric contraction (Carolan & Cafarelli, 1992; Grabiner, Koh, & Miller, 1992). In the current paper the agonist to antagonist ratio (Eq. (1)) was calculated for each individual muscle force (Table 2). It was found that this ratio was statistically significant different ($P < 0.05$) between the healthy and diabetic groups for two dorsiflexors (peroneus tertius, extensor hallucis) and four plantarflexors muscle (gastrocnemius medial head, gastrocnemius lateral head, soleus, peronus brevis). These results have implications and relevance to the area of gait dysfunction in diabetic patients. Kwon, Minor, Maluf, and Muelleremail (2003) indicated that when compared to the healthy controls, patients with diabetic neuropathy show more co-contractions of agonist and antagonist ankle muscles during the stance phase of gait. This agonist–antagonist co-contraction was deemed to facilitate a safer and more stable gait pattern to compensate for diminished foot sensation. For example, Höhne et al. (2012) reported an increased tibialis anterior and decreased gastrocnemius medialis muscle activity during foot flat to mid-stance phase of gait during a simulated sensory neuropathy using transdermal anesthetic injections. This reduced eccentric muscle activity of the gastrocnemius medial head during this phase of gait over time could lead to a decrease in muscle strength when the muscles act as agonist during maximum voluntary ankle plantar flexion.

Based on this study the higher antagonist muscle force was expected since this group of muscles get activated as co-contractors during plantarflexion action. The antagonist muscle force for dorsiflexion action does not seem to reach the same magnitude as that of healthy individuals. On the other hand the fact that antagonist muscle force for plantarflexion muscle group in diabetic patients is higher as compared to healthy controls can be attributed to neuropathy and to the fact that diabetic patients activate their plantarflexion muscles during dorsiflexion action to stabilize their joints. This may indeed be considered as the main reason for the observed increased antagonist muscle force for dorsiflexors group during isometric plantar flexion in diabetic patients as compared to healthy controls that is observed in the current study.

The results of this study could be further explained in the sense that diabetic patients have experience in activation dorsiflexion muscles as antagonist during stance phase of walking. Hence the diabetic patients can effectively deactivate the antagonist muscle during isometric plantar flexion (dorsi flexor group) when there is no need for increasing balance or joint stiffness when sitting and applying force to the dynamometer. On the other hand, diabetic persons do not have experience of performing this task during dorsiflexion and with neuropathy and motor neural impairments they cannot deactivate these muscles. These individuals find deactivation of antagonist plantar flexor muscles more challenging as compared to deactivating antagonist dorsi flexor muscles as they train for the former during stance phase of walking or in standing still.

The ratio of the sum of agonist to the sum of antagonist muscle forces (Eq. (2)) during dorsi-flexion and plantar-flexion was significantly different in the healthy group, while this ratio for plantar-flexion was significantly different for the healthy group compared to the diabetic counterpart (Fig. 1).

In summary, while the ankle muscle strength seems to be consistently and significantly different between the diabetic and healthy participants, the agonist/antagonist muscle force ratio seems to be only significantly different for half of the muscles involved in ankle plantar/dorsi-flexion actions. Because the central nervous system regulates the level of co-contraction of agonist to antagonist muscles, it is likely that motor dysfunction as a result of diabetes and neuropathy may be more pronounced for the muscles for which the agonist/antagonist muscle force ratio was significantly different between the two groups. The ratio between agonist/antagonist muscle forces can be considered as a parameter that show the effectiveness of muscles in producing a high agonist isometric contraction and a low antagonist muscle contraction. While this ratio may be considered as a measure of neuro-muscular capability of individual muscle, the results of this study have implications in quantifying this capacity in diabetic patients.

The results of this study are in line with Mueller et al. (1994) who revealed that diabetic neuropathic patients were unable to generate sufficient ankle joint moment, with a consequent reduction in the dynamic function during walking, resulting in a smaller step length and stride, reducing gait speed and cadence. In the present work it has been shown that the force of gastrocnemius–soleus muscle group as a strong ankle plantarflexors of diabetic patients is reduced by 30% compared to healthy subjects, under isometric plantarflexion. While the force of tibialis anterior, peroneus tertius, extensor digitorum and extensor hallucis were reduced by 26%, under isometric dorsiflexion force. The findings of this study can help in qualified prediction of each individual patient's distal muscle strength. This information can then be used to design interventions at the early phase of the disease which could prevent the accelerated loss of strength and improve quality of life in these patients.

4.1. Limitation of our study

The identification of individual muscle contributions isometric contraction was possible through a detailed analysis of a computer simulation. Some limitations of musculoskeletal modeling and simulation generation and analysis have been described (Neptune, Kautz, & Zajac, 2001; Zajac, Neptune, & Kautz, 2002). It is documented in the literature (Andreassen et al., 2006; Lalli et al., 2013; Orr et al., 2006) important alterations in the muscle fibers histology and neurophysiology, as well in passive tissue properties happen in diabetic population. Therefore, using a healthy model to compute individual muscles force in diabetic individuals will definitely add some errors in the computation. But in the absence of the possibility to measure the individual muscles force directly, estimation of these forces can be valuable. The proposed research methodology in this paper applies only to static conditions, with potential implications in the general diagnosis of the maximum muscle force loss in diabetics.

5. Conclusions

This preliminary study adds to the limited amount of published information on foot and ankle muscle strength in patients with diabetes and increases the knowledge base on the individual muscle force

distribution. The results indicate that patients with diabetes have reduced muscle strength in foot and ankle plantarflexion, dorsiflexion, eversion and inversion, lesser toes flexors, lesser toes extensors, hallux flexors and hallux extensors muscle strength. Consequently it was also found that muscle force for each of the 12 muscles (8 ankle plantarflexors and 4 ankle dorsiflexors) acting on the ankle joint was significantly less in the diabetic group in comparison to the control group. It is likely that the muscles for which the agonist/antagonist muscle force ratio was significantly different between the healthy and diabetic groups, during ankle plantar/dorsiflexion actions were more affected by diabetes and may need more attention during rehabilitation programs. Results from this study provide information for future research in this area.

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References

Abizanda, P., Navarro, J., García-Tomás, M., López-Jiménez, E., Martínez-Sánchez, E., & Paterna, G. (2012). Validity and usefulness of hand-held dynamometry for measuring muscle strength in community-dwelling older persons. *Archives of Gerontology and Geriatrics*, *54*(1), 21–27.

Aggarwal, C. (2013). *Outlier analysis*, *XV*, Yorktown Heights, NY, USA: IBM T. J. Watson Research Center.

Andersen, H., Gjerstad, M., & Jakobsen, J. (2004a). Atrophy of foot muscles. A measure of diabetic neuropathy. *Diabetes Care*, *27*, 2382–2385.

Andersen, H., Nielsen, S., Mogensen, C., & Jakobsen, J. (2004b). Muscle strength in type 2 diabetes. *Diabetes*, *53*(6), 1543–1548.

Andersen, H., Poulsen, P., Mogensen, C., & Jakobsen, J. (1996). Isokinetic muscle strength in long-term IDDM patients in relation to diabetic complications. *Diabetes*, *45*, 440–445.

Anderson, F., & Pandy, M. (1999). A dynamic optimization solution for vertical jumping in three dimensions. *Computer Methods in Biomechanics and Biomedical Engineering*, *2*, 201–231.

Andreassen, C., Jakobsen, J., & Andersen, H. (2006). Muscle weakness: A progressive late complication in diabetic distal symmetric polyneuropathy. *Diabetes*, *55*, 806–812.

Brach, J., Talkowski, J., Strotmeyer, E., & Newman, A. (2008). Diabetes mellitus and gait dysfunction: Possible explanatory factors. *Physical Therapy*, *88*(11), 1365–1374.

Burns, J., Redmond, A., Ouvrier, R., & Crosbie, J. (2005). Quantification of muscle strength and imbalance in neurogenic pes cavus, compared to health controls, using hand-held dynamometry. *Foot and Ankle International*, *26*(7), 540–544.

Carolan, B., & Cafarelli, E. (1992). Adaptations in coactivation after isometric resistance training. *Journal of Applied Physiology*, *73*, 911–917.

Delp, S., Anderson, F., Arnold, A., Loan, P., Habib, A., John, C., et al. (2007). OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, *54*, 1940–1950.

Giacomozzi, C., D'Ambrogi, E., Cesinaro, S., Macellari, V., & Uccioli, L. (2008). Muscle performance and ankle joint mobility in long-term patients with diabetes. *BMC Musculoskeletal Disorders*, *9*, 99.

Giacomozzi, C., D'Ambrogi, E., Uccioli, L., & Macellari, V. (2005). Does the thickening of Achilles tendon and plantar fascia contribute to the alteration of diabetic foot loading? *Clinical Biomechanics*, *20*(5), 532–539.

Grabiner, M., Koh, T., & Miller, G. (1992). Further evidence against a direct automatic neuromotor link between the ACL and hamstrings. *Medicine and Science in Sports and Exercise*, *24*, 1075–1079.

Hajrasouliha, A., Tavakoli, S., Esteki, A., & Nafisi, S. (2005). Abnormal viscoelastic behaviour of passive ankle joint movement in diabetic patients: An early or a late complication? *Diabetologia*, *48*, 1225–1228.

Harbo, T., Brincks, J., & Andersen, H. (2012). Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects. *European Journal of Applied Physiology*, *112*, 267–275.

Hatef, B., Bahrpeyma, F., & Tehrani, M. (2014). The comparison of muscle strength and short-term endurance in the different periods of type 2 diabetes. *Journal of Diabetes and Metabolic Disorders*, *13*(1), 22.

Höhne, A., Ali, S., Stark, C., & Brüggemann, G. (2012). Reduced plantar cutaneous sensation modifies gait dynamics, lower-limb kinematics and muscle activity during walking. *European Journal of Applied Physiology*, *112*(11), 3829–3838.

Ijzerman, T., Schaper, N., Melai, T., Meijer, K., Willems, P., & Savelberg, H. (2012). Lower extremity muscle strength is reduced in people with type 2 diabetes, with and without polyneuropathy, and isassociated with impaired mobility and reduced quality of life. *Diabetes Research and Clinical Practice*, *95*, 345–351.

Krysicki, W., Bartos, J., Dyczka, W., Królikowska, K., & Wasilewski, M. (2006). *Rachunek prawdopodobieństwa i statystyka matematyczna w zadaniach, część 2. Statystyka matematyczna*. Warszawa: PWN.

Kwon, O., Minor, S., Maluf, K., & Muelleremail, M. (2003). Comparison of muscle activity during walking in subjects with and without diabetic neuropathy. *Gait & Posture*, *18*, 105–113.

Lalli, P., Chan, A., Garven, A., Midha, N., Chan, C., Brady, S., et al. (2013). Increased gait variability in diabetes mellitus patients with neuropathic pain. *Journal of Diabetes and its Complications*, *27*(3), 248–254.

Mueller, M., Minor, S., Sahrmann, S., Schaaf, J., & Strube, M. (1994). Differences in the gait characteristics of patients with diabetes and peripheral neuropathy compared with age-matched controls. *Physical Therapy*, *74*, 299–308.

Neptune, R., Kautz, S., & Zajac, F. (2001). Contributions of the ankle plantarflexors to support, forward progression and swing initiation during walking. *Journal of Biomechanics*, *34*, 1387–1398.

Orr, R., Tsang, T., Lam, P., Comino, E., & Singh, M. (2006). Mobility impairment in type 2 diabetes: Association with muscle power and effect of Tai Chi intervention. *Diabetes Care*, *29*(9), 2120–2122.

Pandy, M. (2001). Computer modeling and simulation of human movement. *Annual Review of Biomedical Engineering*, *3*, 245–273.

Park, S., Goodpaster, B., Strotmeyer, E., de Rekeneire, N., Harris, T., Schwartz, A., et al. (2006). Decreased muscle strength and quality in older adults with type 2 diabetes: The health, aging, and body composition study. *Diabetes*, *55*(6), 1813–1818.

Raspovic, A. (2013). Gait characteristics of people with diabetes-related peripheral neuropathy, with and without a history of ulceration. *Gait & Posture*, *38*(4), 723–728.

Stark, T., Walker, B., Phillips, J., Fejer, R., & Beck, R. (2011). Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review. *PMR*, *3*, 472–479.

Thelen, D., & Anderson, F. (2006). Using computed muscle control to generate forward dynamic simulations of human walking from experimental data. *Journal of Biomechanics*, *39*, 1107–1115.

Van den Beld, W., Van der Sanden, G., Sengers, R., Verbeek, A., & Gabreels, F. (2006). Validity and reproducibility of hand-held dynamometry in children aged 4–11 years. *Journal of rehabilitation medicine: Official Journal of the UEMS European Board of Physical and Rehabilitation Medicine*, *38*, 57–64.

Van Schie, C. (2008). Neuropathy:mobility and quality of life. *Diabetes/Metabolism Research and Reviews*, *24*(Suppl.1), 45–51.

Wang, R., & Gutierrez-Farewik, E. (2014). Compensatory strategies during walking in response to excessive muscle co-contraction at the ankle joint. *Gait & Posture*, *39*, 926–932.

Wang, C., Olson, S., & Protas, E. (2002). Test–retest strength reliability: Hand-held dynamometry in community-dwelling elderly fallers. *Archives of Physical Medicine and Rehabilitation*, *83*, 811–815.

Wrobel, J. S., & Najafi, B. (2010). Diabetic foot biomechanics and gait dysfunction. *Journal of Diabetes Science and Technology*, *4*(4), 833–845.

Young, M., Breddy, J., Veves, A., & Boulton, A. (1994). The prediction of diabetic neuropathic foot ulceration using vibration perception thresholds. A prospective study. *Diabetes Care*, *17*, 557–560.

Zajac, F., Neptune, R., & Kautz, S. (2002). Biomechanics and muscle coordination of human walking. Part I: Introduction to concepts, power transfer, dynamics and simulations. *Gait & Posture*, *16*, 215–232.