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Comparison of Limb and Joint Strengths between Tai Chi Chuan Players and Non-Tai Chi Chuan Groups by Using a Force Sensor

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Abstract: Background: Tai Chi Chuan (TCC) is popular in exercise, but little research has been done on limb and joint strength after the exercise. This study aimed to investigate whether TCC players have different limb and joint strengths in the upper and lower limbs from non-Tai Chi Chuan (NTCC). Methods: Twenty TCC players who have at least one year of experience playing TCC were compared with a group of 25 NTCC participants. A force sensor was used to measure forces in the lower and upper limbs. Maximum forces produced by the lower limbs was measured during a standing position with straight legs or were measured in a seated position. The maximum forces produced by the upper limbs were measured in a standing position at elbow and shoulder levels. Results: The forces of the knee extensors in the TCC group were significantly higher (7.4%) than in the NTCC group; however, the forces of the knee flexors in the TCC group were significantly lower than the NTCC group. The heel-force in hip extension in the NTCC group was significantly higher (9.3%) than in TCC; the toe-force in the plantar flexion in the NTCC was significantly higher than in the TCC group. There were no significant differences between the two groups in the hand-forces in the upper limbs. Conclusions: TCC routine movements strengthen the muscles related to knee extension, which are mainly related to bending knee performance during TCC exercise. For the healthy people between 42 and 78 years old, TCC benefits the enhancement of the strength for knee extension but not for the knee flexion, ankle plantar flexion and hip extension. There is no significant difference between the TCC and NTCC groups on the strength of upper limbs and joints. As a whole, the effect of Tai Chi Chuan exercise on the strengths in the limbs and joints is compromised. In the future, a study with larger sample size than this study is highly recommended.

Keywords: force sensor; Tai Chi Chuan; joint strength; lower limbs; upper limb

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1. Introduction

Musculoskeletal, neuromuscular, cardiorespiratory, balance and movement functions are all reduced with advancing age. However, this decline may be prevented or slowed down by physical exercise [1]. Clinically, patients with movement disorders need to do a reasonable amount of exercise for rehabilitation. Tai Chi Chuan (TCC) is a form of traditional Chinese martial art and has been considered beneficial for physical fitness [2–5].

Tai Chi Chuan, more commonly known as Tai Chi, performs a complex series of movements with an emphasis on body, breathing and mental focus [6]. Several studies have classified TCC as moderate exercise, and its intensity involves no more than 55% of maximum oxygen intake and does not exceed 60% of maximum heart rate [7,8]. Taylor et al. [2]

reported that TCC improved balance and muscle strength. Also, single leg standing (SLS) and semi-squat positions are usually included in TCC exercise that may increase lower extremity muscle strength [9]. In 2010, TCC was strongly recommended by the American Geriatric Society and the British Geriatric Society as an effective treatment showing good evidence for decreasing falls among the elderly and improving health outcomes [10,11]. Li et al. [12] stated that, during the past 40 years, TCC has flourished throughout Western countries. Recently, TCC has become popular worldwide, and it has been the topic of many research studies. Indeed, many studies have examined the effectiveness of TCC on the lower limb muscles and balance in healthy or patient populations [13,14]. However, there is a lack of research that directly measures limb and joint strengths.

The roles of the muscles during TCC change between contraction and relaxation, movers and stabilizers and weight-bearers and non-weight bearers [15]. During the TTC performance, semi-squatting is considered the most used posture that can occur with different amounts of contraction, such as eccentric, concentric and isometric contractions that cause a large load on the muscles of the lower limbs [16]. A cross-sectional study examined the knee muscle strengths between 24 elderly TCC experienced people and 24 elderly people with NTCC experience. The study found that TCC participants had higher peak torque-to-body weight ratios in concentric isokinetic contractions of the knee extensors and flexors than NTCC participants [17]. Moreover, Xu et al. [3] conducted a cross-sectional study to investigate the influence of TCC and jogging on muscle function in the lower extremities of older people. Results showed that 21 of TCC and 22 joggers generated greater torque in the ankle dorsiflexors than the control group. Also, the knee extensors and flexors muscle strength were higher in both groups compared to the control group, but the knee extensors muscle endurance of TCC was more pronounced than the control group. Previous studies have used isokinetic dynamometers, such as Cybex Norm dynamometer (Cybex, Medway, MA, USA), BiodexSystem3Pro isokinetic muscle strength testing instrument (New York, NY, USA), Weider bank (model Pro 330, Leeds, UK) and hand-held dynamometer [18–23] to measure the muscle strength and endurance of the knee flexors and extensors and muscle strength and endurance of the ankle dorsiflexor and plantar flexor muscles. However, these instruments have some disadvantages. For example, these devices take up space in labs, are expensive and need an experienced technician for use, and the participants should get training by the therapists to get the most valid results. Therefore, the present study employed a Force Sensor (FS) device to measure limb and joint strengths. FS is not expensive, small in size, lightweight, portable, very sensitive in reading, easy to use and measures forces in three directions.

The elderly can suffer from falls resulting from limb and joint weakness, especially the muscles and soft tissues around the ankle joint [24,25]. TCC practitioners have improved muscle strength, particularly in the elderly [3]. However, little research has directly measured limb and joint strengths in TCC groups, and it is still unclear whether the TCC group is better than the NTTC group regarding limb and joint strength. Previously, most studies measured the knee extensors/flexors muscle strength, and little research has investigated the ankle plantar flexors/dorsiflexors and the hip joint strength; neither have studies measured the hand pushing force for TCC practitioners. In movements, the forces produced by the limbs are related to muscle strengths in the joints. Traditionally, Tai Chi has been considered to improve the upper limbs, but there is no evidence. It was why this study would provide initial evidence for the upper limbs as well. So far there is no research study that has used the FS to measure the upper and lower limb and joint strengths. Hence, this present study attempted to fill the research gap by measuring limb and joint strength in the upper and lower limbs using specific joint movements for the TCC group. The aim of this study was to investigate whether TCC would be an effective rehabilitation exercise to improve health, especially for the healthy, by measuring limb and joint strengths using the FS device and by comparing the TCC and NTCC groups.

2. Materials and Methods

2.1. Participants

Two groups of healthy volunteers were recruited, 20 Tai Chi Chuan (TCC) practitioners from Tai Chi Chuan clubs, and 25 volunteers who have never practiced Tai Chi Chuan as a control group. This study was not limited to a specific range of age and thus included those who were (a) age 40 years and above; (b) could walk independently without walking aids; (c) were able to engage in daily living activities independently during the study period; and (d) were in general healthy condition with no apparently reported problems, e.g., amyotrophy or injuries. The TCC group came from three clubs where they practice under the guidance of a qualified TCC Master. The masters usually have a lot of experience in playing TCC. In the cohort, one of the masters has played 15 years and 7 months, and another has played 29 years. Previous studies also reported that TCC masters are significantly better than NTCC [8,26]. The TCC group was invited by volunteer recruitment posters, which were circulated by the Master of each club. The NTCC group was recruited by volunteer recruitment posters, which were displayed at the local hospital, sport center and sports fitness clubs. University staff and students were randomly invited via an email to be participants as the control group. Written informed consent was obtained from all participants prior to conducting the study. This study was approved by the University of Dundee, School of Medicine Research Ethics Committee, following the tenets of the Declaration of Helsinki (SMED REC 033/17).

The TCC group consisted of 20 TCC players with at least one year of TCC experience. At the time when the data was collected, they had played TCC for a mean 11 years with Standard Deviation (SD) 10.02, ranging between 1 and 33 years. They normally practiced TCC every day for approximately one hour. The practice session began with warm-up stretching exercises, then TCC routine practice, followed by a cool-down exercise. There were no significant differences between the two groups in age, gender, body mass and height (Table 1).

Table 1. Baseline characteristics of the participants in the study.

	TCC (*n* = 20)	NTCC (*n* = 25)	Min–Max
Gender (M/F)	9/11	11/14	
Age (years)	59.55 (2.01)	59.56 (1.79)	42–78
Body mass (kg)	75.37 (3.49)	74.62 (3.00)	50–119
Height (cm)	167.69 (1.64)	166.77 (1.79)	150–183

Note: TCC, Tai Chi Chuan; NTTC, Non-Tai Chi Chuan; F, female; M, male; Min, Minimum; Max, Maximum; Mean (Standard Error of Mean or SE). All $p > 0.05$.

2.2. Force Sensor (FS) Device

Force Sensor (FS) Model 6A68D was supplied by Interface Force Measurements Ltd. (Scottsdale, AZ, USA) (Figure 1A). The reasons why we selected this device were that (1) it is portable and easy to set in different positions and (2) the sensor can measure a wide range of forces and moments, covering the demand of this project. The FS measures the force and torque values in three-dimensional space. It is usually used in industrial and scientific applications, such as medical research (orthopedics and biomechanics). It contains three axis forces and three torques or moments of the axes (Fx, Fy, Fz, Mx, My and Mz), and thus it is called a 6-axis sensor. It measures all parameters simultaneously in three perpendicular axes and exports six-channel outputs (Table 2).

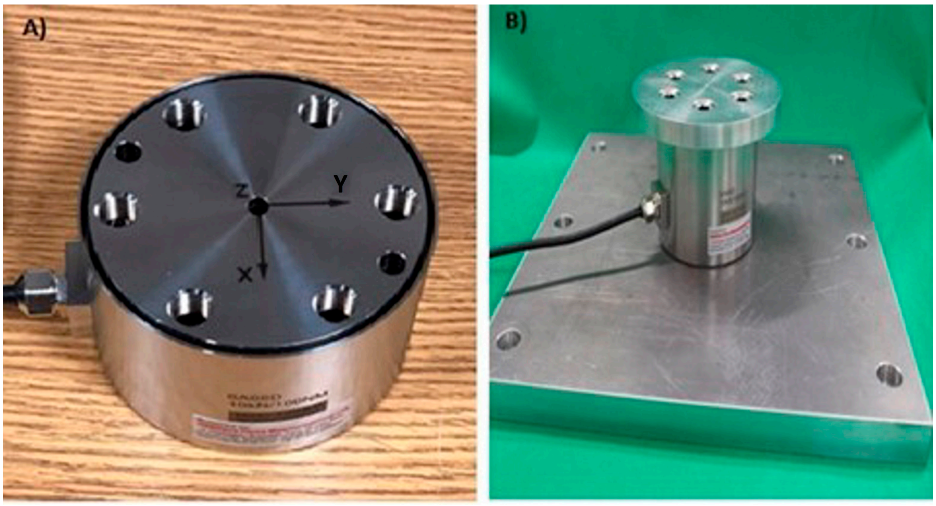

Figure 1. (**A**) Force Sensor (FS) device, (**B**) Force Sensor with the top and base parts.

Table 2. Force Sensor Model 6A68D Characteristics.

The Force Sensor Characteristics			
Fx (N)		Max to 10 kN	
Fy (N)		Max to 10 kN	
Fz (N)		Max to 20 kN	
Mx (Nm)		Max to 100 Nm	
My (Nm)		Max to 100 Nm	
Mz (Nm)		Max to 100 Nm	
Diameter		83 mm	
Height		64 mm	
Mass		1.050 kg	
Materials		Stainless Steel (SS)	
Specifications *			
Accuracy class	0.2%		
Relative linearity error	0.1%FS		
Relative zero signal hysteresis	0.1%FS		
Temperature effect on zero signal	0.1%FS/K		
Temperature effect on characteristic value	0.05%RD/K		
Relative creep	0.1%FS		
Relative repeatability error	0.5%FS		
Nature frequency	3.3 kHz		
Mounting Details			
Live End		Dead End	
Threads	M10 × 1.5 6 Places 12 mm Deep	Mounting Screws	M10 × 1.5 6 Places 12 mm Deep
Dowel Pin Holes (mm)	6 H7 2 Places 12 mm Deep	Dowel Pin Holes (mm)	6 H7 2 Places 12 mm Deep

*: The data was from the website of Interface Force Measurement Solution [27] and personal communication with the staff of the company. Nature frequency is the response time.

2.3. Force Sensor (FS) Device Preparation

In order to use the FS in our measurements, the top and base parts were added (Figure 1B). The parts were designed by using Autodesk (Fusion 360 software). Both parts were made from Stainless Steel (SS) with smooth surfaces. The first part is the top one that is considered from double circle shapes or circles with two faces attached together with two different measurements and is 17 mm in height. The first circle or the first face of the circle (the bottom circle) in the top part diameter is 78 mm to be sure that is appropriate with the FS device diameter with 5 mm height. This circle is attached to the Live End Mounting Surface. The second circle or second face of the circle (the top circle) in the top part diameter is 120 mm to suit hand and foot measurement and is 12 mm height to be suitable with M10 socket cap bolt height. The top part of the FS device was made to be more appropriate when a hand or foot is applied to it to measure the resultant muscle forces. The second part is a square shaped base part with dimensions of 300 × 300 mm and a height of 20 mm. In the middle of the base part, there are 6 holes of 16.6 mm with 12 mm deep, then 10 mm with 8 mm depth from the bottom to fix the FS device on it. Also, there are six threaded holes surrounding the base allowing it to be fixed on a wall or chair (Figure 1B). The FS device was adjustable in height position on the wall and chair so that participants felt comfortable during measuring. Each posture/muscle group was measured five repeated times. The protocol allowed us to obtain reliable readings.

2.4. Model-BX8-HD44 Amplifier

The model BX8 amplifier for the 6-axis sensor comprised a stand-alone measurement system with ±10 V analog outputs on each of the six channels.

2.5. Force Platform

A force platform (FP) was used to test FS. The FP was AMTI BMS400600 (Watertown, MA, USA), and the measured ranges are max 2225 (N) in x and y axes, 4450 (N) in z axis (vertical direction) and measurement accuracy ±0.5% of applied load (e.g., 225.63 N).

Body Mass

The body mass was measured using a general medical scale (SECA model 798, Germany) in our hospital. The scale has accuracy with ±0.1 kg in range of up to 100 kg and ±0.2 kg in range between 100 kg and 200 kg during calibration. The differences between body weight and FS or FP are 0.8% as all readings. It should be noted that this scale has been used for many years in our hospital and may have errors in data collection. Therefore, the differences between weights and FS/FP readings were from the scale.

2.6. The Reliability of the Force Sensor

The reliability of the FS was tested by measuring nine subjects with different weights. The participants were measured by using both a force platform in our gait lab and the FS Model 6A68D, respectively. The participants stood still on the FS or force platform and the weights were recorded for 5 s. The average weights from all participants were statistically compared as Table 3.

In this study, we aimed to compare FS (Force Sensor) and FP (Force Platform) so that we could use FS in the experiment, as FP is widely considered a golden standard in biomechanics labs. The SECA scale used is an ordinary device, which has been used in our hospital for many years, and thus may have the unpredicted errors. The SECA readings were used as test data for two instruments (i.e., FS and FP) for the comparison between FS and FP rather than between FS/FP and SECA. In the test, the subjects could have stood on FS and FP to get two sets of readings directly.

Table 3. Reliability of the force sensor.

No.	Body Mass (kg)	Weight (N)	FS (N)	FP (N)	W & FS diff%	W & FS abs diff%	W & FP diff%	W & FP abs%	FS & FP diff%	FS & FP abs diff%
1	50.9	499.33	477.4	476.9	4.39	4.39	4.49	4.49	0.11	0.11
2	65.7	644.52	643.2	642.8	0.20	0.20	0.27	0.27	0.07	0.07
3	67.4	661.19	664.7	661.2	−0.53	0.53	0.00	0.00	0.53	0.53
4	68.1	668.06	670.8	671	−0.41	0.41	−0.44	0.44	−0.03	0.03
5	71.7	703.38	695.7	695.9	1.09	1.09	1.06	1.06	−0.03	0.03
6	83	814.23	813.6	814	0.08	0.08	0.03	0.03	−0.05	0.05
7	90	882.9	876.8	876.4	0.69	0.69	0.74	0.74	0.04	0.04
8	94.6	928.02	932.4	931.6	−0.47	0.47	−0.39	0.39	0.09	0.09
9	103.6	1016.3	1016.5	1014	−0.02	0.02	0.23	0.23	0.25	0.25
mean	77.22	757.55	754.57	753.76	0.56	0.88	0.67	0.85	0.11	0.13
SD					1.54	1.36	1.51	1.41	0.18	0.16

In Table 3, the equation of (A − B)×100/A was used to calculate difference percentage. The mean of abs difference% between weight and FS or FP readings are roughly 0.88% or 0.85%. Two instruments gave similar differences consistently. These differences between the instruments and scale may come from the old scale. It is noted that the difference between FS and FP as the mean of abs difference% is 0.13%, which is reasonably good. In other words, FS is fine to be used in our experiment. Further, the FS and FP readings was used to run a "reliability analysis" in SPSS to get a Cronbach's Alpha 1.000 and Interclass Correlation Coefficient (ICC) as 1.0, meaning that the reliability is fine. The Pearson Correlation Coefficient was 1 as Figure 2.

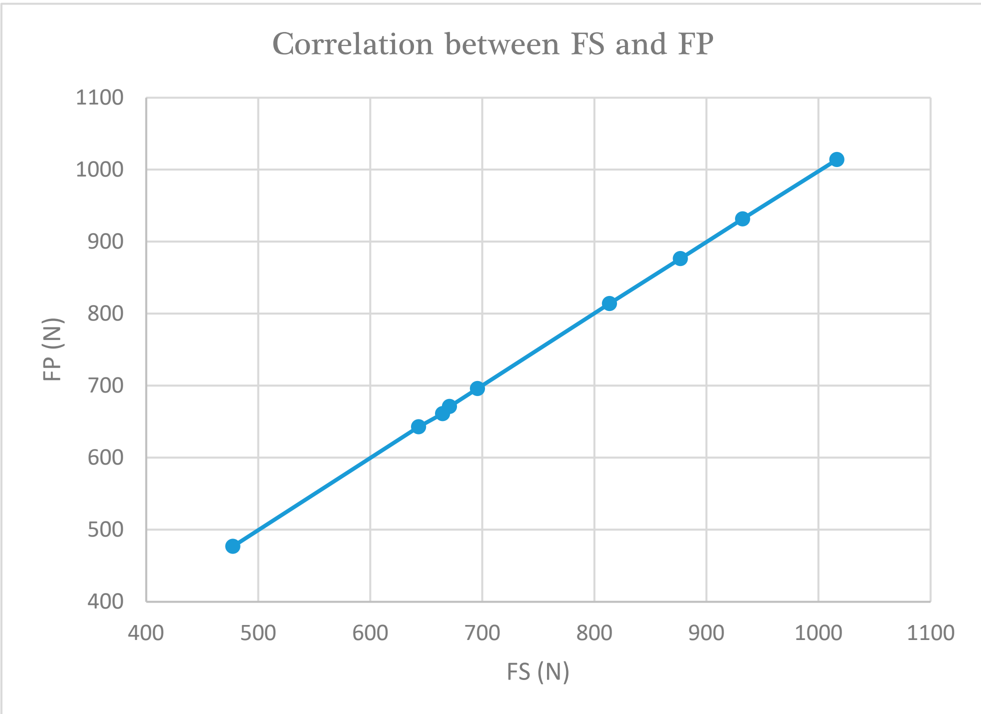

Figure 2. Linear correlation between FS and FP readings. The Pearson correlation coefficient is 0.999, $p < 0.0001$.

Following Table 3, the readings were further dealt with in Table 4. Using Table 4, we used a classical statistical method (Bland and Altman) [28] to ascertain repeatability or agreement between the FS and FP readings, and the results show that the difference range of 95% CI (confidence interval) are between 0.81–1.96 × 1.32 to 0.81 + 1.96 × 1.32, i.e., −1.8

to 3.39, where 0.81 and 1.32 are mean and SD of differences (Table 4). If the difference is related to the readings' means, we can estimate that the differences have 95% CI within 0.35%, i.e., (2 × 1.32 × 100/((754.56 + 753.75)/2)), where 754.56 and 753.75 are the means of FS and FP readings (Table 4). FS and FP show no significant difference in readings indicating that FS is a valid, reliable tool to be used in the data collection, like FP.

Table 4. Repeatability analysis of the force sensor.

No.	FS (N)	FP (N)	FS-FP (N)
1	477.4	476.9	0.50
2	643.2	642.8	0.40
3	664.7	661.2	3.50
4	670.8	671	−0.20
5	695.7	695.9	−0.20
6	813.6	814	−0.40
7	876.8	876.4	0.40
8	932.4	931.6	0.80
9	1016.5	1014	2.50
mean	754.57	753.76	0.81
SD			1.32

2.7. Testing Protocol

In our research, there were eight measurements to be measured, including six measurements for the lower limb and joint strengths (the foot forces with the movements of hip flexion or extension, knee flexion or extension and ankle plantar flexion or dorsiflexion) and two measurements for the upper limb and joint strengths (the hand pushing forces with specific postures in the elbow and shoulder joints). The participants were instructed to push the FS device as much as possible for five trials in each measurement using their dominant leg and hand. Each participant practiced each measurement before data were formally collected. The FS was reset to zero before each trial.

Participants were required to attend the Motion Analysis Laboratory, Tayside Orthopedics and Rehabilitation Technology Center, Ninewells Hospital and Medical School, University of Dundee for one single testing session. Each session lasted approximately two hours, and the participants supplied their own sportswear (shorts and t-shirt) and were barefoot.

Upper-limb dominance was determined by asking volunteers to write their name and sign a consent form while lower-limb dominance was determined by asking the volunteer to kick a ball three times. Then, anthropometric measurements of height and weight were measured and recorded.

In measurements of lower limb and hip joint strength, participants were asked to stand in a comfortable posture and to push the FS using their heels or toes. The FS was attached to a wall, and participants applied force forwards by their toes or backwards by the heels, according to participant requirement of height. When pushing the FS, participants were required to keep the lower limbs as straight as possible. Participants were asked to push the FS using their heel backwards from a standing position with hip and knee extended to measure the toe forces when the hip joint moved in flexion, and the participant applied the force as much as possible (Figure 3 left). Participants were then asked to push the FS using their heel backwards from a standing position to measure the heel forces when the hip joint moved in extension (Figure 3 right). It should be noted that these measuring ways are different from the traditional ways that use isokinetic dynamometers, and it is also recognized that the lower/upper limbs and other joints also take part in the movements and make some degree of contribution to the readings.

Figure 3. Measurement of toe- or heel-forces when participants stood and performed hip flexion (**left**) or extension (**right**).

For measuring of knee muscle strengths, participants were asked to push the FS device forwards using their forefoot from a seated position with their foot on the wooden step, maintaining 90° in the knee and hip joints and the ankle joint on the natural position (Figure 4). In addition, participants were asked to push the FS, positioned under the chair, using their heel backwards in the knee joint at 90° and in the ankle joint at natural position (Figure 4). Participants were then instructed to push the FS from a seated position with 90° at the knee and hip joints and neutral position of the ankle joint downwards from motor electric adjustable height multifunction. As participants had different leg lengths, they were required to maintain the knee at 90° and to push FS in plantar flexion and dorsiflexion (Figure 5).

Figure 4. Measurement of the toe- or heel-forces when participants sat with the knee extension (**left**) or knee flexion (**right**).

In measurements of ankle muscle strength, participants were asked to use their toes to push the FS device on the wall upwards from a seated position with their heel on a furring strip board to maintain the ankle joint in the neutral position and 90° in the knee joint to measure toe-force in dorsiflexion (Figure 5 left) and to use their forefoot to push the FS device on the ground downwards with their heel on a vertical board to maintain the ankle joint in the neutral position and 90° in the knee joint to measure heel-force in plantar flexion (Figure 5 right).

Figure 5. Measurement of Ankle dorsiflex (**left**) and ankle plantar flexor (**right**).

After measuring the lower limbs, the FS device was then positioned at participant elbow level and fixed to the wall. Participants were instructed in a standing position with 90° at the elbow joint and neutral position in the shoulder joint to push the FS as forcefully as possible using their hand/palm to measure hand pushing force (Figure 6 right). The FS was then moved to participant shoulder level and again fixed to the wall. Participants were instructed in standing position with shoulder flexion 90° and arm extended to push the FS as forcefully as possible using their hand/palm to measure hand pushing forces (Figure 6 left).

Figure 6. Hand forces with the shoulder joint in 90 deg with the trunk (**left**) and hand pushing forces with the elbow joint in 90 deg (**right**).

2.8. Data Analysis

After processing the data in the multichannel device, the ASCI (*.csv) files were processed through a custom-built software program using Matlab®. This software was used to extract the maximum force. The demographic variables for participants were tabulated using Microsoft® Excel®. All variables were presented as means and standard errors. Statistical software SPSS (v 28) was used to carry out statistical analysis. A general linear model with multivariate in SPSS was used to determine significant differences between the two groups. The general linear model for multivariate procedure provides the analysis for multiple dependent variables by one or more factors. All five trials for each participant were analyzed, as the general linear model method allowed to deal with multi-measure and input subject index as an interactive factor. Using this procedure, we could test null hypotheses about the effects of factor on the means of various groupings of a joint distribution of dependent variables. This method allows us to test a group of variables at one run. The $p \leq 0.05$ was set at a statistically significant level.

3. Results

3.1. Hip Joint

The mean of heel maximum force in the TCC group was significantly lower than the NTCC group during hip extension ($p = 0.046$). No significant differences in toe maximum force were observed between the two groups during hip flexion (p = 0.824) (Table 5 and Figure 7).

Table 5. Maximum force of lower limb and hand muscles strength (N).

Maximum Force		Mean	Std. Error	95% Confidence Interval		*p*-Value
				Lower Bound	Upper Bound	
Foot force in ankle dorsiflexors	TCC NTCC	123.04 120.63	4.42 3.95	114.34 112.84	131.75 128.41	0.684
Hand Pushing force in elbow 90°	TCC NTCC	78.48 76.28	2.93 2.62	72.70 71.12	84.25 81.45	0.578
Heel force in hip extension	TCC NTCC	93.40 102.13	3.25 2.91	86.99 96.40	99.81 107.86	0.046 *
Toe force in hip flexion	TCC NTCC	113.62 112.56	3.56 3.18	106.62 106.29	120.63 118.83	0.824
Toe force in knee extension	TCC NTCC	175.98 162.20	5.21 4.66	165.71 153.03	186.24 171.38	0.049 *
Heel force in knee flexion	TCC NTCC	77.74 92.17	3.19 2.86	71.44 86.54	84.03 97.80	0.001 **
Foot force in ankle plantar flexion	TCC NTCC	122.33 133.09	3.90 3.49	114.64 126.21	130.02 139.97	0.041 *
Hand pushing force in shoulder 90°	TCC NTCC	81.74 83.84	2.59 2.32	76.63 79.28	86.84 88.41	0.545

* The mean difference is significant at the 0.05 level; ** The mean difference is significant at the 0.001 level.

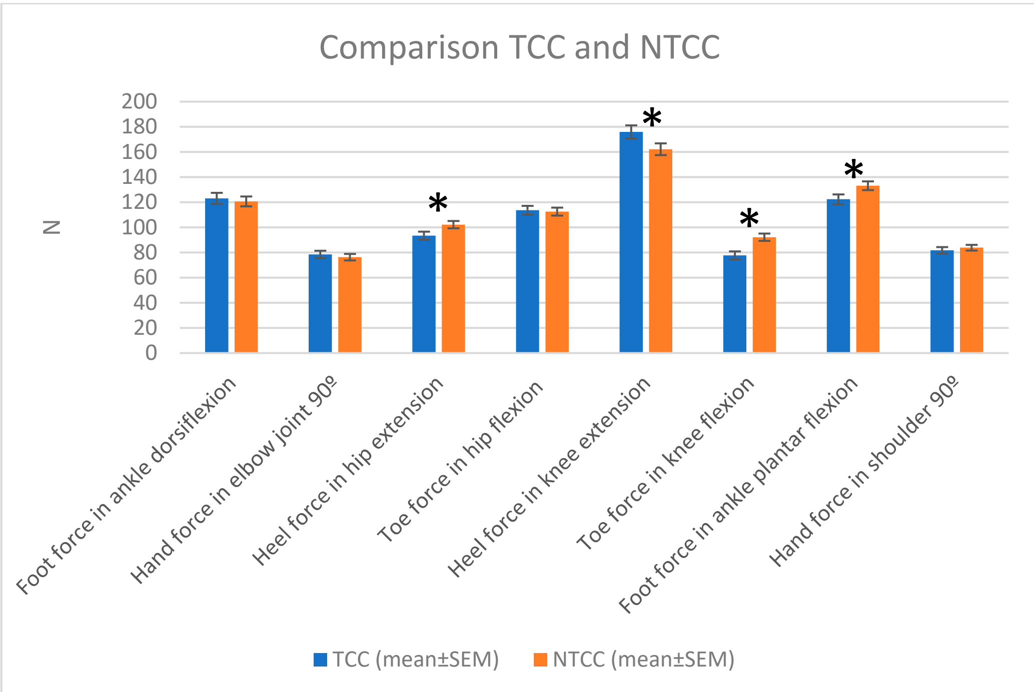

Figure 7. Comparison of the measured forces between TCC and NTCC groups. Note: * $p < 0.05$.

3.2. Knee Joint

In the knee extension and flexion, the foot forces showed significant differences between the two groups. The heel maximum force showed that participants in the TCC group generated more force than NTCC group in the knee extensor muscle strength

(p = 0.049), while the toe maximum forces were significantly lower in the TCC group than the NTCC group (p = 0.001) during knee flexion (Table 5).

3.3. Ankle Joint

The foot maximum force was greater in the NTCC group during plantar flexion, whereas that did not show any significant differences between the two groups during dorsiflexion (Table 5).

3.4. Hand Pushing Forces with Upper Limbs and Joints

There were not any significant differences between the two groups in the hand maximum forces either in the shoulder joint at 90° (p = 0.545) or in the elbow joint at 90° (p = 0.578) (Table 5).

4. Discussion

Previous studies have used different devices, such as hand-held dynamometer, Cybex Norm Dynamometer and Biodex, to measure the lower limb muscles [18,19,22,23]. In this present study, a FS device was used to measure the limb and joint strengths, and all lower and upper limb joints were measured. It is the first study to complete all measurements for the TCC group. It should be noted that the measuring ways in this study were done when participants stood or sat naturally and thus different from the traditional ways using isokinetic dynamometers. It is also understood that various muscles other than the primary agonist(s) may contribute to a specific movement and affect the readings.

4.1. Knee Joint

The foot forces in knee extension and flexion significantly differed between the two groups. The maximum force in knee extension showed that the participants in the TCC group generated higher force (175.98 N) than NTCC (162.20 N) (p = 0.049) by roughly 7.4%, while the TCC showed that the maximum force (77.74 N) in knee flexion was significantly lower than the NTCC group (92.17 N) (p = 0.001) by roughly −18.5%. The TCC players were stronger than the NTCC practitioners in knee extensor muscles strength but not in knee flexors. In the literature, the previous results were contradicted or mixed. Most studies reported that knee extensor strengths were increased with a range from 10–40% [Wu et al., 2002; Xu et al., 2006; Pereira et al., 2008; Zhuang et al., 2014; Zuo et al., 2019] [3,21,29–31], but some reported no significant change [Song et al., 2003; Jin et al., 2003; Yang et al., 2021] [32–34]. In our opinion, the TCC players usually use a semi-squatting position during practice that causes large loading on the lower limb joints, and the squatting requires TCC players to maintain bending the knees stably; thus, knee extensors are enhanced. This point was supported by some studies [3,21,29–31], but not by others [32–34].

4.2. Ankle Joint

Although most TCC forms require a dorsiflexion posture, there was no significant difference between the two groups in the ankle joint strengths in dorsiflexion. It is found that the foot force in plantar flexion was significantly different between the two groups in that the NTCC group were stronger than the TCC group.

The foot maximum forces in ankle plantar flexion were greater in the NTCC group (133 N) than in TCC (122 N) by roughly 8%, whereas that in ankle dorsiflexion did not show any significant differences between the two groups. The TCC practitioners during TCC performance do ankle dorsiflexion most of the time, but in this study, there was no significant difference between the two groups in ankle strengths in dorsiflexion. However, the foot maximum forces in plantar flexion in the NTCC subjects were stronger than the TCC group. In the literature, a few of the previous studies reported that ankle flexors and extensors had higher strength in the TCC group than in the control one, with a range between 10% and 25% [Zhuang et al., 2014; Zou et al., 2019] [29,31], while other studies on TCC have not done too much on ankle strength. The reason for the results should be further investigated in the future.

4.3. Hip Joint and Hand Pushing Forces

The maximum heel force in hip extension in the TCC group was significantly lower than in the NTCC group by roughly −9.3%, but there were no significant differences in toe maximum force in hip flexion between the two groups. There were not any significant differences between the two groups in the hand maximum forces either in the shoulder joint of 90° or in the elbow joint of 90° as in Table 4. These results indicate that the TCC exercise had no effect on the upper limbs and joints in terms of wrist forward flexion strength. In the literature, there is little research on the hand pushing forces; thus, it is impossible to compare our results with others.

One of the most interesting findings in this study was that a significant difference was found for the heel forces in hip extension between the two groups. The NTTC participants had greater heel forces in the hip extension than the TCC group. It may be the reason that TCC players emphasize movements with the hip flexion muscles rather than hip extension muscles during TCC.

Another interesting finding is that there was no significant effect of TCC practice on the hand pushing forces in either the shoulder or elbow joints of 90°.

It should be noted that previous studies used different means to measure TCC muscle or joint strength, e.g., a hand-held dynamometer to measure grip forces, a jump to estimate joint powers or various types of isokinetic dynamometers to measure the joint strengths as torque. These methods had different types of outcomes, e.g., torque (Nm) from isokinetic dynamometers with different joint angles. In our study, limb/joint strength is measured as force (N) directly. As the device used in measurements and the variables (and units) used in this study are different from those from the previous studies, it is difficult to compare our results with previous ones. That said, we estimate the joint moment using the force and leg length and then compare our numeric outcomes with previously published studies. Using the estimated moment, the knee extension moments are 77 ± 2.4 (Mean ± Standard error of mean) in TCC and 71 ± 2.15 Nm in NTCC, and the knee flexion moments are 34 ± 1.5 and 41 ± 1.4 Nm, respectively. These results are slightly lower than those in Wu et al. (2002) [30] and similar to Zhuang et al. (2014) [31]. Nevertheless, most of the previous studies reported that knee exteriors had higher strength in the TCC than in control groups, which is the same as what we observed from this study.

Recently, some studies have investigated TCC in various aspects. Ko et al. (2020) reported that the TCC group was able to jump 44% higher than the NTCC group. During the jumping, the TCC group also showed a lower Centre of Mass (CoM), larger Range of Motion (RoM) in joint angle and higher joint moment and power than NTCC [4]. Further, Ko et al. (2022) compared four age groups during jumping and found that the jumping heights decreased with aging [5]. Fong et al. (2022) reported that the knee extensor and flexor in children with developmental coordination disorder were improved after 3 months of TCC exercise [35]. Sadacharan (2022) showed that the muscle functions in sedentary older adults with chronic condition(s) were improved with TCC [36]. Zhang et al. (2022) observed that the foot pressures in participants with knee osteoarthritis were changed after 6 months of TCC [37]. These studies obtained some meaningful results. However, the strengths in the joints and limbs between TCC and NTCC have not been directly measured and compared. Therefore, this present study would fill the research gap.

4.4. Limitation

There are a few of limitations in this study. The sample size was small, and thus, this study is considered as a pilot one. The participants covered the age range only between 42 and 78, and the elderly above 80 years old were not included. It is recognized that this study did not measure the muscle strength directly for muscle groups, and various muscles other than the primary agonist(s) may contribute to a specific movement; thus, the force readings include the total effect of involved muscles on the posture. In the future, a new study should consider a unique posture and constraints for a single group of muscles so that FS could measure specific strength for a group of muscles.

In summary, it was found that the TCC practitioners showed higher force than NTCC in the knee extensor muscles. On the other hand, NTCC practitioners showed higher forces than TCC, with significant differences in the heel force in hip extension, knee flexion and ankle plantar flexion. A major reason that could explain the discrepancy is that the TCC practice emphasizes a crouch posture, which relies on the hip flexion, knee extension and ankle dorsiflexion rather than on the hip extension, knee flexion and ankle plantar flexion. So, there is no significant effect of TCC practice on the hand pushing forces at the shoulder or elbow of 90°. Further studies could be designed to explore muscle electronic activities, i.e., electromyograph during TCC movement.

This study introduces a novel measurement device and its application in rehabilitation. From this study, a few points were obtained: (1) This device is flexible and portable in measurement setting-up; (2) this device helped to measure the strengths of the limbs and joints and some of the measurements are firstly done and reported in this research field; (3) this applied study helped to understand the TCC exercise in more detail than previous studies from a new angle; and (4) the method provided by this study could be applied in the assessment of other exercises in rehabilitation.

5. Conclusions

This research study confirmed that we can use FS to measure limb and joint strengths in the lower and upper limbs when participants stand or sit naturally. Tai Chi Chuan participants show benefit on the knee extension muscle strength but not benefits on the knee flexion muscles, ankle plantar flexion muscles and hip extension muscles. There is no difference between the TCC and non-Tai Chi Chuan groups on hand pushing forces either in the elbow or shoulder joints of 90°. As a whole, the effect of Tai Chi Chuan exercise on the strengths in the limbs and joints is compromised. In the future, a study with a larger sample size than this study is highly recommended.

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