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Knee joint biomechanics of simplified 24 Tai Chi forms and association with pain in individuals with knee osteoarthritis: A pilot study

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Abstract

Objectives: Tai Chi (TC) is a multi-beneficial exercise for improving health and function in knee osteoarthritis (OA). Biomechanical insights of 24 TC forms at the knee joint are not well understood. We aimed to examine knee joint biomechanics of TC actions form by form and their interactions with pain in individuals with knee OA.

Methods: Ten knee OA participants were recruited. Their full body motion during performance of 24 TC forms was collected. The knee joint biomechanics were determined by using an inverse dynamic approach based on collected full body kinematics and kinetics. In addition, the knee joint pain level was scored during each TC form. The joint moments were compared between walking trials and each TC form. The relationship between knee joint biomechanics and pain scale was assessed.

Results: The knee adduction moment for five TC forms was different from the walking trial. The knee extension moment for 21 TC forms differed from the walking trial. For TC trials, the knee extension moment, but not the adduction moment, was positively correlated with pain level. Similarly, the knee extension moment was moderately proportional to pain level during the walking trials, but not the adduction moment.

Conclusions: Our pilot results explored the knee joint biomechanics profiles of individual TC forms and examined their associations with knee joint pain. The findings in this study could provide scientific basis to select the best TC forms for the purpose of reducing knee joint pain among individuals with knee OA.

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Credit author statement

Dr. Liu contributes to the conception and design of the study and takes responsibility for the integrity of the work, from inception to finished article. Authors Yang and Liu take responsibility of the integrity of the data and the accuracy of the data analysis. *Study concept and design*: Liu. *Acquisition of data*: Liu. *Analysis and interpretation of data*: Liu and Yang. *Drafting of the manuscript*: Yang and Liu. *Critical revision of the manuscript of important intellectual content*: Liu and Yang. *Statistical analysis*: Yang.

Declaration of competing interest

The authors have no conflicts.

Keywords

Tai Chi; Knee Joint Biomechanics; Pain; Knee Osteoarthritis

1. Introduction

Knee osteoarthritis (OA) is a leading cause of adult disability, with 27 million affected individuals in the United States [1]. The pathology of knee OA includes intra-articular inflammation, collagen degradation, and frequent abnormal mechanical loading of the knee; these are associated with abnormal mechanical and biological consequences [2]. Disabilities that arise from typical impairments of knee OA include decreased muscle strength, reduced range of motion, and decreased aerobic cardiovascular function [3]. Dysfunction resulting from knee OA affects performance of daily activities, independent functioning, and quality of life. The effects of OA are especially prevalent in older populations [1], in which routine daily activities including walking and sit-to-stand movements can be difficult [4]. It is imperative to develop programs which can alleviate joint pain among people with knee OA.

Tai Chi (TC) is an ancient Chinese tradition and involves a series of sequentially performed component movements which incorporate uninterrupted, slow, and rhythmic weight-bearing activities in loading and unloading fashion. The most common TC practice is simplified Yang style 24 forms [5]. As TC has been proven to improve balance, muscle strength, and joint flexibility and knee OA has been identified as a risk factor of reduced balance and falls in older adults [6], TC could be a particularly well-founded intervention for people with knee OA.

Studies that applied TC to people with knee OA have reported inconsistent results in improving physical functions (such as strength, balance, etc.) [7]. A potential factor leading to such diverse results could be the different forms used in previous studies. The individual TC forms used in prior studies were chosen without specifying a quantitative and objective standard. Therefore, those selected TC forms were not based on knowledge of the biomechanical load acting on the knee during performance of individual TC forms. To maximize the training effect of TC-based intervention targeting people with knee OA, it is critical to select the most beneficial forms. A prerequisite to identify the optimal TC forms is a comprehensive understanding of the biomechanical profile of each TC form.

Similar issues were presented in studies employing TC to reduce the knee pain level for people with knee OA. The rules of selecting TC forms were not clear, possibly resulting in inconclusive findings among studies [8]. A possible selection system of TC forms for alleviating knee pain is to check if the knee joint biomechanical measurement (like joint moments) is related to the pain level. If such a correlation exists, it will not only provide us an objective way to quantify the pain level, but a system to identify the TC forms which are most beneficial to reduce the knee pain for individuals with knee pain. To our best knowledge, the association between the biomechanical profile and knee joint pain levels of TC forms among individuals with knee OA remain completely unexplored. Such a knowledge gap severely impedes progress towards development of an optimal TC-based program for knee OA. We believe that if TC can be selected based on biomechanical principles for reduction of knee joint pain, the benefits of TC could conceivably be enhanced.

The purpose of this pilot study was twofold: 1) to quantify the biomechanical load of the knee joint during performance of simplified 24 Yang-style TC forms, and 2) to determine whether the load is associated with knee joint pain. By doing so, our findings would fill the knowledge gap regarding mechanistic insights of TC forms in knee OA. The well-understood mechanisms could facilitate the design of effective TC-based interventions for reducing pain in people with knee OA.

2. Methods

Ten individuals with mild to moderate knee OA (seven females, mean ± SD age: 65.1 ± 12.0 years; height: 1.67 ± 0.12 m; mass: 83.8 ± 26.3 kg) participated in this study. The inclusion criteria were: 1) individuals aged 40 years and older, 2) meeting American College of Rheumatology criteria for symptomatic Knee OA [9], 3) experiencing the presence of pain/tenderness over the medial region of the knee, and 4) having had no TC experience prior to this study. Persons with the following conditions were excluded from participating: 1) a history of lower extremity joint replacement, 2) any intra-articular knee injection (steroid, hyaluronic acid) within the previous six months, 3) report of a heart condition or chest pain during periods of activity or rest, 4) currently seeking or receiving physical therapy for knee OA, and 5) a medical condition precluding the participant from undergoing physical activity or biomechanical gait analysis. All participants signed an informed consent document approved by the Institutional Review Board.

Through one-on-one instruction from an experienced TC instructor, participants learned how to perform each of the 24 TC forms correctly over 2 weeks (i.e., four randomly picked forms per session in one day, three sessions weekly). At the end of each session, participants performed the respective TC forms following 5–7 regular walking trials. Their fullbody kinematics of the walking and TC trials were collected from 37 reflective markers placed on the body’s bony landmarks [10] using a motion capture system (Vicon, UK). Ground reaction force was recorded synchronously with the kinematic data by four force plates (AMTI, MA). After the practice of the TC forms, participants were asked about their pain level at the knee joint in the OA side while performing TC. The measurement was conducted using the visual analog scale (VAS), a validated, subjective measure for chronic pain [11].

The last trial of regular walking and each TC form performance during the test in each session were selected as the representative trials to be analyzed. Marker paths were low-pass filtered with a cutoff frequency of 6 Hz using a 4th order, zero-lag Butterworth filter. The center of pressure (COP) trace during stance phase was determined from the ground reaction force. An individualized seven-segment human model that included the head-arms-trunk, bilateral thighs, legs, and feet, was developed for each participant [12]. Resultant moments of the lower extremity joints were calculated using an inverse dynamics approach based on the collected ground reaction forces and COP data. The peak value of knee adduction (KA) and extension (KE) moments in the OA side was determined and normalized to body mass (Nm/kg).

SPSS 24 (IBM) was used for conducting all analyses. A significance level of 0.05 was applied throughout unless otherwise specified. Both KE and KA moment were tested for skewness using the Shapiro-Wilk test. If data violated the normal distribution, a logarithm transform was executed. Both moments were compared between the average of all selected walking trials and each of the 24 TC forms using paired *t*-tests. To reduce Type I error due to the multiple *t*-test comparisons, the Bonferroni step-down (Holm) correction was made to the significance level. Pearson's correlation analyses were used to determine the association between KA or KE and pain level for both TC and walking trials.

3. Results

One participant withdrew from the study after learning 12 TC forms and another dropped out after the first session. Their available data were used for the correlation analyses but excluded from the paired *t*-tests.

Both joint moments exhibited differences between the walking trial and the TC forms. Specifically, the KA moment for five TC forms (Forms 1, 3, 14, 17, and 23, *p*-values ranging between 0.044 and < 0.001) was different from the walking trial while the remaining 19 forms showed no difference from the walking trial (*p*-values ranged between 0.052 and 0.909, Fig. 1a). The KE moment for all but three TC forms (*p*-values ranging between 0.022 and < 0.001 except Forms 3, 11, and 12, where $p = 0.058$–0.128) differed from the walking trial (Fig. 1b). For TC trials, the KE moment ($r = 0.549$, $p < 0.001$), but not the KA moment ($r = 0.094$, $p = 0.178$), was positively correlated with the pain level (Fig. 2 a-b). Similarly, the KE moment was moderately proportional to the pain level ($r = 0.356$, $p = 0.01$, Fig. 2d) during the walking trials, but not the KA moment ($r = 0.115$, $p = 0.423$, Fig. 2c).

4. Discussion

TC forms consist of a series of sequentially performed movements. TC for knee OA, whether performed as an exercise alone or woven into daily life, should be based on concrete mechanisms which soundly explain the health benefits of TC practice. This study is the first to directly investigate knee joint biomechanics and pain association of individual TC forms among adults with knee OA. Our results indicate that the knee joint moments vary widely among TC forms (Fig. 1). In addition, the knee joint pain level is linearly associated with the peak KE moment but not the peak KA moment (Fig. 2).

Previous biomechanical studies of TC mainly focused on essential and basic TC movement such as TC gait or step [13]. They examined temporal and spatial measures of TC gait, such as stride length; basic kinematic of lower extremity; and kinetics, such as joint moment of the lower extremities during TC gait. Despite being meaningful, previous studies provide little information about the differences in joint load between TC forms. The lack of such information presents a barrier to the selection of the most effective TC forms for pain reduction in people with knee OA. By contrast, our study uniquely expanded the current knowledge base of the biomechanics of TC, particularly in the knee joint, using form by form analysis. The current study systematically examined knee joint biomechanics of individual forms and indicated that TC forms had different knee joint load patterns than walking. The results suggest that musculoskeletal responses vary with individual TC forms. The observed variation could be a confounding factor that may explain the inconsistent results produced by previous studies on the efficacy of TC training in people with knee OA [7].

To our knowledge, our study also is the first attempt to directly explore the relationship between knee joint biomechanics and pain during performance of TC. Our results are consistent with previous studies indicating that KE moment is strongly associated with knee joint pain during walking [14]. The current study extends the correlation between KE moment and joint pain in people with knee OA to TC forms. TC has multiple components of sequential movements in multiple planes, our results clearly demonstrate that different TC forms with different magnitudes of KE moments are strongly associated with pain. This positive association would suggest that lower sagittal plane knee moment may have a protective effect against pain. The lower magnitude of KE moment would reduce the mechanical demand on the knee joint, which may in turn reduce the abnormal mechanical stress on the medial compartment of the knee joint and thus the pain level.

Our results also showed that adduction moment is not proportional to the knee joint pain level during walking and TC actions. TC have higher range of motion of the knee with similar ground reaction support compared to walking [10,13], and TC showed different dynamic stability compared to walking [15], which suggests that TC involves a greater amount of weight-shifting in the frontal plane, with higher mechanical demand in the sagittal plane. Our results imply that knee moments in the frontal and sagittal planes may have different mechanisms of modulating knee joint contact stress. More studies are needed to investigate such mechanisms.

Our pilot study has limitations. First, the sample size was relatively small. It is thus possible that our results may have a great variation in the outcome measurements affecting our findings. The small and unbalanced sample size between genders restricted us from considering sex as a factor in our analyses. Second, we did not incorporate healthy control participants in this study, although we used walking as a control to compare with individual TC forms. Third, there could be inconsistency in learning TC forms performance among participants due to the large range of age, body types, or physical capacity in the present study. However, our individualized approach for delivering the TC training could reduce such inconsistencies. All limitations warrant further investigations with a larger sample size.

Our study represents a clinically meaningful and critical step towards the establishment of the biomechanical mechanism of TC in knee OA. Our approach provides a unique opportunity to select the best TC forms for pain reduction and design optimized TC-based rehabilitation programs for knee OA in the future.

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APPENDIX.

List of Simplified 24 Tai Chi forms

Form 1: Commencing Form

Form 2: Part the Wild Horse's Mane on Both Sides

Form3: White Crane Spreads Its Wings

Form 4: Left and Right Brush Knee and Push Forward

Form 5: Playing the Lute

Form 6: Repulse Monkey Left and Right

Form 7: Grasp Sparrow's Tail Left

Form 8: Grasp Sparrow's Tail Right

Form 9: Single Whip

Form 10: Wave Hands Like Clouds

Form 11: Single Whip

Form 12: High Pat on Horse

Form 13: Right Heel Kick

Form 14: Strike to the Ears with Both Fists

Form 15: Turn and Left Heel Kick

Form 16: Left Lower Body and Stand on One Leg

Form 17: Right Lower Body and Stand on One Leg

Form 18: Fair Lady Works with Shuttles

Form 19: Needle at Sea Bottom

Form 20: Fan Through the Back

Form 21: Turn Body, Deflect, Parry, and Punch

Form 22: Apparent Closing a Door

Form 23: Cross Hands

Form 24: Closing Form

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Significance and innovations

- This is the first study to quantify the knee joint biomechanics profiles of individual TC forms during TC practice in knee OA. This would provide insight into our understanding of the movement strategies used in TC.
- Our results provided direct evidence of the musculoskeletal responses of the human body during TC and demonstrated a measurable biomechanical signal of TC at the knee joint (the extension moment), which was associated with pain in knee OA.
- Our pilot study established a scientific foundation for future efforts to refine the most effective TC forms for knee OA rehabilitation.

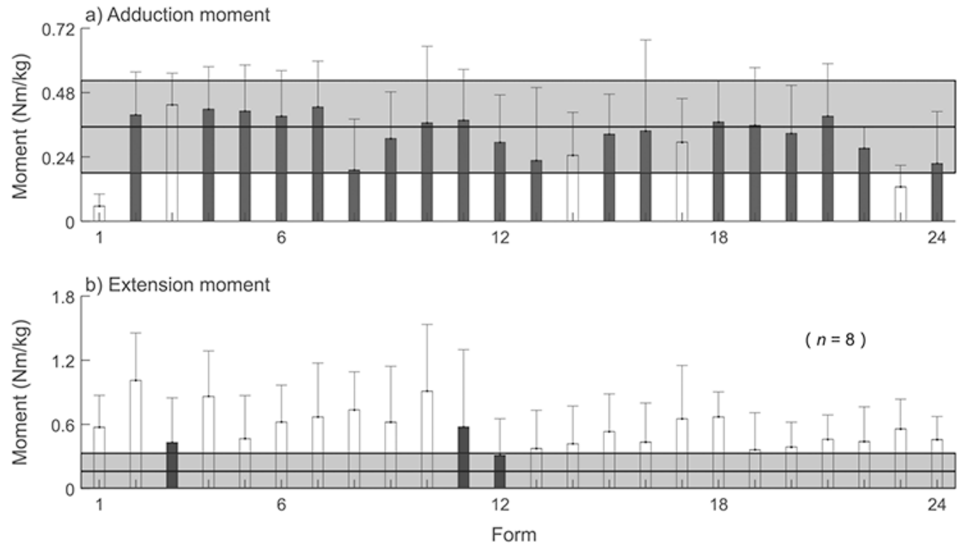

Fig. 1.

Comparisons between each of 24 TC forms and walking for a) the peak knee adduction moment and b) peak knee extension moment. The moment is normalized to the body mass. The gray band indicates the mean ± standard deviation of the knee moment during regular gait. The black bars indicate that the corresponding TC forms are not significantly different from walking trial.

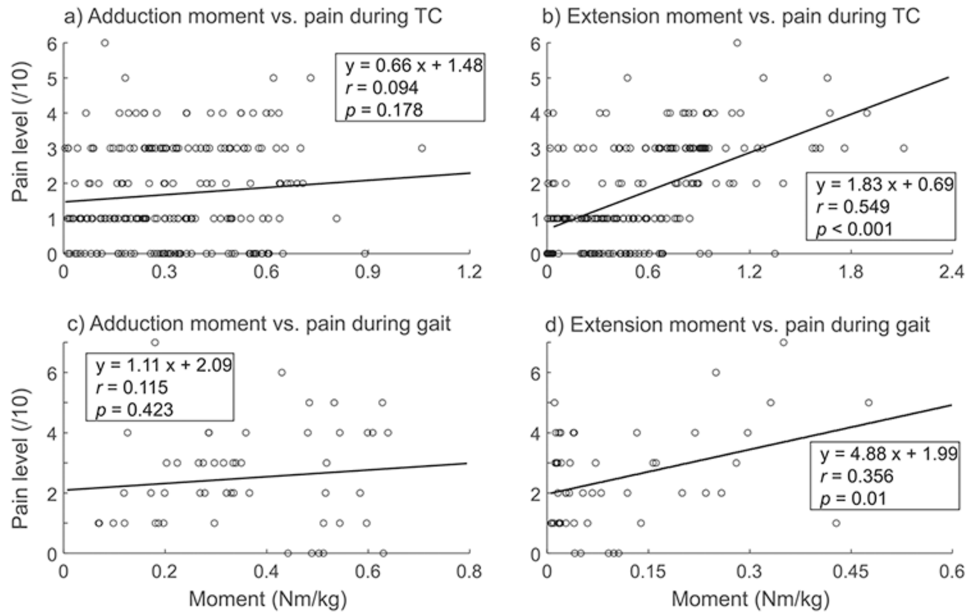

Fig. 2.

Scatterplot with line of best fit of the pain level versus (a) the peak knee adduction moment during TC forms, (b) peak knee extension moment during TC forms, (c) peak knee adduction moment during regular gait, and (d) peak knee extension moment during regular gait among people with knee OA. The moment is normalized to the body mass. The pain level was measured by visual analog scale (VAS) on a scale of 0–10. Also shown are the regression equation ($y = kx + b$), Pearson's correlation coefficient (r), and the significance level (p) for each linear regression model.