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Knee Biomechanical Characteristics of Knee Unfriendly Movements in 42-form Tai Ji

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To the Graduate Council:

I am submitting herewith a thesis written by Chen Wen entitled "Knee Biomechanical Characteristics of Knee Unfriendly Movements in 42-form Tai Ji." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Kinesiology.

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ABSTRACT

Tai Ji was one of recommended non-pharmacologic treatments for knee OA, but it is not clear that if all of the Tai Ji movements would be suitable and beneficial for knee OA patients. The purpose of this study was to examine 1) GRF and knee kinematic and kinetic characteristics of the identified knee unfriendly Tai Ji movements including lunges, pushdown, kick and pseudo-step 2) effects of high- and low-pose of these movements on those characteristics, and 3) compare biomechanical variables between the Tai Ji movements and slow waking. Seventeen volunteers performed three trials in each of eight movement conditions: high and low lunges, high and low pushdown, high and low kick and toe-touched pseudo-step and slow walking. The peak knee extensor moment was 67.3%, 94.0% and 97.9% greater in the low-pose lunge, pushdown and kick than those of high-pose movements ($p<0.001$ for all comparisons). The high-pose also caused a reduced peak knee abduction moment ($p=0.004$) and knee adduction ROM ($p<0.001$) in lunge. Greater peak knee extensor moments were found in all Tai Ji movements of both poses, except for high pose kick, compared to slow walking ($p<0.001$). Based on the results, the high-pose position would be more suitable for Tai Ji participants with knee OA than low-pose. Further study may be needed to demonstrate effects of high-pose Tai Ji training in managing pain and physical functions of knee OA patients.

Keywords: Tai Ji, Tai Chi, knee abduction moment, knee ROM, knee OA, slow walking

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CHAPTER I

INTRODUCTION

Osteoarthritis (OA) is one of the most common types of arthritis (31). It has been reported that 46% of U.S. adults suffer from painful knee OA in at least one leg by age 85 years (31). Knee OA symptoms greatly limit the patients' ability in daily tasks such as standing up, walking and running, and stair ascent and descent. The presence of knee OA has a great influence on kinematic and kinetic gait parameters (2, 3, 22, 58, 59). Knee OA patients typically walk slower than healthy people to decrease the knee pain (59) and showed a more extended knee joint position compared to the health subjects during heel strike (30). Additionally, many previous studies have demonstrated that the peak knee external adduction moment significantly increases in knee OA patients (2, 22, 30, 58, 59).

Tai Ji, as a mind-body therapy, is a traditional Chinese martial art that contains natural posture, gentle and smooth movements (41). It has become a popular activity around the world regardless of age, gender, or race. According to the American College of Rheumatology, the recommended treatment for knee OA is a combination of non-pharmacologic and pharmacologic therapies which have intended to improve patients' physical function, manage pain and improve their quality of life (14). Tai Ji has also been recommended as one of the non-pharmacologic treatments among others such as the usage of assistive devices and acupuncture (41). Several studies have demonstrated positive effects of Tai Ji on balance control, muscle strength, flexibility, cardiovascular and respiratory function (8, 11-13, 25, 42). Tai Ji has also been widely used in rehabilitation of neuromuscular (55, 56) and cardiovascular diseases (21, 43).

In recent years, Tai Ji has been shown to relieve pain and improve the quality

of life for knee OA patients (6, 23, 40, 47). Most Tai Ji training programs have shown improvement in both the Western Ontario and MacMaster Universities Osteoarthritis Index (WOMAC) (5) and visual analog scale (VAS) (16) for pain (6, 33, 40, 47).

There are only a few biomechanical studies on Tai Ji available in English literature. Mao and the colleagues (27-29) performed a series of kinematic studies regarding the lower extremities movements of 42 –form Tai Ji. Seven support patterns and six step directions were classified. The double-limb support patterns showed the longest duration percentage of total duration among others due to the needs of balance control during movements (28). It was reported that during Tai Ji movements, anterior and medial plantar regions showed greater loading than other regions (27). In addition, the mediolateral displacement for the center of pressure (CoP) was greater in Tai Ji movement than in normal walking. Wu and colleagues (51-53) performed several biomechanical studies related to Tai Ji gait which is widely involved in all styles of Tai Ji. For kinematic studies, longer gait cycle duration, greater range of motion in lower extremity joints and smaller plantar pressure difference between forefoot and rearfoot were showed in Tai Ji gait compared to normal walking (50, 52). For kinetic study, the ankle showed smaller peak plantar flexor moment than normal gait (53). Knee peak external adductor moment was greater in Tai Ji gait than normal gait.

Statement of the problems

Tai Ji has gained great popularity in the U.S. and the rest of the world due to its health benefits (57). However, there are only a few biomechanical studies on Tai Ji available in the English literature (50, 51, 53, 54). Although several biomechanical studies have been conducted on Tai Ji gait (50-53) and some support patterns of Tai Ji movements (28, 29), to date most of the movements have not been

investigated. It is not clear that if all the Tai Ji movements would be suitable and beneficial for knee OA patients. Some previous Chinese studies have reported that practicing Tai Ji can cause knee pain in healthy elderly people (60). In order to understand the potential benefits and risks to the knee joint of each movement in 42-form Tai Ji, a comprehensive qualitative analysis of the movements is necessary. Furthermore, identifying movements that may be harmful to the knee (knee unfriendly movements) could help in movement selection and design of Tai Ji exercise routines for knee OA patients. More importantly, analyzing kinematic and kinetic characteristics of the identified knee unfriendly Tai Ji movements provide scientific results for Tai Ji exercise design and movement selections for knee OA population and fill the void in the Tai Ji literature.

Therefore, the purposes of this study were twofold. The first one was to conduct a qualitative study of 42 movements in 42-form Tai Ji to identify several lower extremity movement elements (common elements in several forms of Tai Ji) that are knee unfriendly. Based upon the initial assessments, four common movements were identified, including multiple lunge, push down, kick and pseudo-step. The second purpose was to exam the GRF and knee kinematic and kinetic characteristics of the identified knee unfriendly movements and the effects of different height of pose (high and low) on biomechanical characteristics.

Hypothesis

There were two hypotheses for this study:

1) In multiple lunge, push down, horse stance and kick movements, the peak knee extensor moment would be greater than those in low speed walking.
2) The high pose movements would show smaller knee extensor moment than low pose movements.

Limitations

1. Subjects only performed four identified Tai Ji movements. Their performance may be different from those performed continuously during entire 42-form Tai Ji.
2. Subjects may have performed Tai Ji movements differently in the lab setting than they practicing by themselves.
3. Only 42 - form Tai Ji was investigated.
4. The upper extremity movements were ignored.
5. The accuracy of 3D kinematics data collecting was highly related the accuracy of the placement of retroreflective anatomical markers on the surface of the joints.
6. The foot tracking markers were placed on the shoe. The foot movement within the shoe may not be captured precisely.

Delimitations

All participants were healthy, active and had no previous serious lower extremity injuries. The exclusion criteria included:

1. Knee pain for at least 6 months during daily activities when squat down.
2. BMI greater than 35.
3. Lower back pain referred to the lower limbs.
4. Unable to see, hear, or follow instructions.
5. Inability to squat down.
6. Any neurologic disease (e.g., Parkinson's disease)

Chapter II

Literature Review

The purpose of this study was to examine GRF and knee kinematic and kinetic characteristics of knee unfriendly movements that are commonly involved in 42-form Tai Ji and to evaluate the effects of different heights of poses on those characteristics. After this study, the suggestion will be given to knee osteoarthritis (OA) patients to avoid or modify knee unfriendly movements when practicing Tai Ji. This literature review includes three main sections: knee osteoarthritis, benefits of Tai Ji, and biomechanics studies of Tai Ji.

Knee Osteoarthritis

Gait characteristics of knee osteoarthritis patients

Knee OA is known as a common form of OA that loses the cartilage cushioning of the knee joint (31). Continual high pressure on the knee joint and its surrounding tissue cause deterioration of articular cartilage and meniscus. In severe osteoarthritis, complete loss of the articular cartilage causes friction between bones, induces pain and limits motion (36). Joint pain of OA is usually worse with the passing of time. It was reported that nearly one in two, or 46% of U.S. adults may develop painful knee OA in at least one knee by age 85 years (31). Knee OA symptoms greatly limit a patients' ability to complete daily tasks such as standing up, walking and running, and stair ascent and descent. Three-dimensional biomechanical gait analysis is a well-accepted method to understand the biomechanical factors that may be involved in the progression of knee OA (1). The presence of knee OA has a great influence on kinematic and kinetic gait parameters (2, 3, 17, 22). Knee OA patients typically walk slower than healthy people to decrease their knee pain (59) and

their knees are in a more extended position than a healthy subject during heel strike (30). Additionally, many previous studies have demonstrated that the peak knee external adduction moment significantly increases in knee OA patients (2, 22, 30, 58, 59).

Several previous studies investigated the effects of walking speed on gait characteristics of knee OA patients. Landry et al. (22) compared the differences in gait parameters between a self-selected speed and 150% of the self-selected speed. They found that OA patients had a greater peak external adduction moment than healthy subjects for both walking speeds. There were no significant differences between the two walking speeds in the adduction moment. Increased speed caused an increase in the knee flexion moment and external rotation moment. However, the OA patients showed smaller flexion moment and external rotation than control subjects. In addition, the faster walking speed resulted in greater knee flexion angle during the swing phase.

Zeni and Higginson (59) also investigated differences in gait characteristics of knee OA patients at three walking speeds (self-selected speed, 1.0 m/s, and fastest tolerable speed). Based on Kellgren-Lawrence (KL) severity levels, the subjects were classified into three different groups: healthy control (KL grade 0), moderate OA (KL grade 2 or 3), severe OA (KL grade 4). There were significant differences between the groups for theself-selected walking speed ($p=0.008$). Compared to the healthy controls (1.22 ± 0.14 m/s), both moderate (1.13 ± 0.12 m/s) and severe (1.03 ± 0.26 m/s) knee OA patients showed slower self-selected walking speed. Healthy controls (1.75 ± 0.23 m/s) also showed faster fastest tolerable speed than moderate OA (1.50 ± 0.21 m/s) and severe OA groups (1.37 ± 0.28 m/s), respectively. Significant differences in gait characteristics were found between self-selected and fastest

tolerable speed. Knee joint reaction force, peak vertical ground reaction force (GRF) and its loading rate increased with the increased walking speed from 1m/s to fastest tolerable speed. The severe OA group showed smaller external knee adduction moment at 1.0 m/s speed compared to the self-selected speed ($p=0.031$).

Furthermore, Zeni and Higginson (58) also investigated how knee OA affects individual joints' contributions to the total support moment. They found that knee OA patients reduced their knee contribution to the support moment at 1.0 m/s and self-selected speed. The ankle demonstrated greater contribution to the support moment in OA group compared with healthy controls. Finally, they concluded that the walking speed was not related to joint contribution; rather the change was due to the neuromuscular accommodation of the joint pain or muscle weakness.

Kinematic variables were also compared between knee OA patients and healthy controls during walking. Mundermann et al. (30) reported that the knee OA patients showed a more extended knee joint position than the healthy subjects during heel strike. The knee OA patients walk 16.5% slower than the healthy control subjects (59). Kaufman et al. (17) reported that knee OA patients had approximately six degrees less peak knee flexion angle than healthy controls. In addition, during the stance phase, Linley et al. (26) reported that knee OA patients showed a significant drop in the pelvis on the swing side due to the weakness of the hip abductor muscles. This causes a lean of the trunk toward to the swing limb thereby increasing medial compartment loading in the knee.

Gait kinetic characteristics have also been examined with many studies reporting that the peak knee internal abduction moment significantly increases in knee OA patients (2, 22, 30, 58, 59). Kaufman et al. (17) investigated the gait characteristics of knee OA patients during level walking. A flexor moment was

observed at heel strike then followed by an extensor moment. During the late stance, a clear flexor moment was found. Patients with OA showed smaller peak extensor moment than and significantly increased peak adduction moment compared to healthy subjects. Thorp et al. (44) reported that during the mid-stance and late stance phase, the peak knee adduction was 24% greater in the moderate OA group than mild OA group. The author also reported knee adduction angular impulse was greater during both mid-stance and late stance phase for both mild and moderate knee OA patients than subjects without knee OA. Atephen et al. (2) reported that knee OA patients showed 36.5% smaller early stance flexor moments and 47.6% greater mid-stance external varus moment in the knee joint compared to healthy subjects. Severe knee OA patients showed 71.4% smaller knee extension moment and 36.8% lower internal rotation moment during late stance phase compared to moderate knee OA patients.

Treatment of Knee Osteoarthritis

In 2012, the American College of Rheumatology recommended several nonpharmacologic and pharmacologic therapies in osteoarthritis of the lower extremities (14). A technical expert panel (TEP) including academic and practicing rheumatologists, physicians, occupational and physical therapist recommended that OA patient should participate in aerobic exercise, such as Tai Ji (41) and aquatic exercise, in order to improve their aerobic capacity. The recommendation also includes land-based resistance exercises program and balance training program. For knee OA patients who are overweight, TEP highly recommends weight loss activities. Recommended non-pharmacologic treatments also included the usage of assistive devices, such as joint splints, medial wedge insoles for valgus knee OA (38), subtler strapped lateral insoles for varus knee OA (35), knee braces and walking aids.

In conclusion, knee OA patients showed significantly different gait kinematic and kinetic parameters from healthy individuals due to the joint degeneration. They walked slower (59) and at a more extended knee position (30) than asymptomatic subjects. Many studies have also demonstrated the peak external knee adductor moment (internal knee abduction moment) significantly increased in the knee OA patients (2, 17, 22, 30).

Tai Ji

Tai Ji (also referred as Tai Chi), as a mind-body therapy, is a traditional Chinese martial art that contains natural posture, gentle and smooth movement (41). It has become a popular activity around the world regardless of age, gender or race. Zhang Sanfeng initially devised Tai Ji in the thirteenth century A.D. (18) and after hundreds of years and so many changes, various styles of Tai Ji have been developed. Major styles include Sun, Chen, Wu and Yang styles (10). Each style has its own distinctive features, but the basic principles remain the same. 42-form Tai Ji combines the typical movements from all major styles of Tai Ji, and is widely used in national and international Tai Ji competition (28). Several studies have demonstrated the health and fitness benefits from participating in Tai Ji for prevention of falls, and improvements of muscle strength, flexibility, cardiovascular and respiratory function (8, 11-13, 25, 42).

General benefits of Tai Ji

Gatts et al. (13) randomly assigned 22 balance-impaired seniors to two groups: a Tai Ji program training five days per week for 1.5 hours per day and a non-exercising control group. All the subjects were asked to walk barefoot along a 10m walkway at a self-selected speed before and after the three-week training program.

They found that Tai Ji training significantly enhanced balance responses by more efficacious use of mechanisms controlling stepping strategies of the swing leg during walking. Anterior- posterior center of mass path significantly increased after Tai Ji training ($p < 0.017$). Tai Ji training also improved neuromuscular responses controlling the ankle joint during perturbed gait (12).

Takeshima et al. (42) reported that healthy older Japanese adults had a significant improvement in arm-curl strength, chair stand, and up-and-go tests after they participated in a Tai Ji program two days per week for 12 weeks. Li et al. (25) found that 25 elderly participants in a 16-week Tai Ji program significantly increased the muscle strength of knee flexors ($p < 0.001$) and significantly decreased semitendinosus muscle latency ($p = 0.014$) after training.

Chang et al. (8) recruited 54 patients with coronary artery disease, 22 of them participated in a weekly 90 minute Yang's style Tai Ji program for six months, while 32 patients received usual care only. All the subjects completed a treadmill exercise test before and after the six-month training program. Their blood pressure and heart rate were monitored during the treadmill test. Those in the Tai Ji training program showed a 10% reduction in in peak rate-pressure product and a 18.7% reduction in rate-pressure product reserve, which indicated that Tai Ji training may lead to a better prognosis for patients with coronary artery disease. The control subjects did not show any differences after six months.

Chen (11) recruited 41 elderly men who resided in long-term care facility to test a newly developed simplified Tai Ji program which was 50 minutes per session, three times per week for six months. All the subjects underwent resting blood pressure measurements, one-leg-stand test, sit-and-reach test, and handgrip strength test before and after six months of training. The participants had a 4.3 % drop in

systolic blood pressure (p=0.002) and a 6.6 % drop in diastolic blood pressure (p<0.001), and improvements in handgrip strength (2.4 kg, p<0.001) and lower body flexibility (1.9 cm, p=0.006).

Tai Ji benefits on Knee OA

Tai Ji has gained increasing popularity as a knee OA treatment. Normally pain is measured by the participant's self-reported level of pain he or she experiences by filling out a visual analog scale (VAS) survey. The Western Ontario and MacMaster Universities Osteoarthritis Index (WOMAC) survey is also used to assess pain, stiffness, and physical function for hip and/ or knee OA. There are also some simple tests that can be used to measure participant's physical function, such as a 6 minute walking test, 10-meter walking test, timed-up and-go test and timed stair ascent and descent. The Short Form-36 (SF-36) consisting of physical and mental components has also been used to measure health-related quality of life.

Lee et al. (23) had fourteen elderly knee OA patients complete an eight week Tai Chi Qigong training program involving sixty minute sessions twice a week. Thirty knee OA patients who did not receive any Tai Ji training were in the control group. The participants in the Tai Chi Qigong program showed a significant decrease in 6-meter walking test time (Tai Chi: -1.6 ± 1.7 s versus control: -0.2 ± 0.8 s, P < 0.01), and a significant improvement in SF-36 summary (Tai Chi: 21.6 ± 16.8 versus control: 9.8 ± 13.6, P < 0.05).

Shen et al (40) assessed physical function in 40 elderly knee OA patients after six weeks of instructed Tai Ji training that consisted of one hour per sessions, two times per week. After the Tai Ji training, stride length, stride frequency and gait speed significantly increased 2.6%, 2.2% and 5.7% respectively. Furthermore, pain significantly decreased, overall WOMAC as well as the subscales of pain, stiffness,

and physical function were improved ($p < 0.001$) and the maximum VAS pain scale score also significantly decreased ($p = 0.002$).

Brismee et al. (6) recruited 41 adults with knee OA and randomly assigned them to either a Tai Ji intervention or an attention control group. The Tai Ji intervention included six weeks of three sessions per week, 40 minutes per Tai Ji session, followed by another six weeks of home-based tai chi training, finally there was a six-week detraining period. The subjects in the attention control group attended six weeks of health lectures following the 12 weeks of normal daily activity. The intervention group showed significant decreases in mean overall knee pain ($p = 0.008$), maximum knee pain ($p = 0.004$) and the WOMAC subscales of physical function ($p = 0.008$) and stiffness ($p = 0.021$) compared to baseline. The Tai Ji intervention group also reported lower overall pain (30%, $p = 0.0089$) and better WOMAC overall (27.8%, $p < 0.05$) than the attention control group at weeks nine, respectively. However, all the improvements disappeared after six weeks detraining.

Wang et al (47) reported that Tai Ji is effective for treating knee OA. Forty knee OA patients were randomly assigned to a twelve week Tai Ji training group that consisted of 60-minute sessions twice weekly or an attention control group that included wellness education and stretching program. Compared to the control group, after 12 weeks of training, the training group showed significant improvement in WOMAC pain (313%, $p < 0.001$) and physical function score (178%, $p = 0.001$), 180% greater improvement in VAS score ($p = 0.002$), on average 10.9 second faster chair stand time ($p < 0.001$) and SF-36 physical function component ($p = 0.004$).

Ni et al (33) used thirty-five Chinese women with knee OA. They were randomly assigned to either a 24-week Tai Ji program or an attention control group. The subjects in the Tai Ji group practiced the 24-form simplified Yang- style Tai Ji

with frequency gradually increased, two days per week for the first eight weeks, three days per week for the second eight weeks, and four days per week for the third eight weeks. During the 24-week training, the subjects in control group attended wellness education and stretching section. After 24 weeks, the subjects in the Tai Ji group showed a 262% greater improvement in the WOMAC total score ($p<0.001$) compared to control group, as well as pain ($p=0.001$), stiffness ($p=0.043$) and function subscale score ($p<0.001$). They also showed improvement in physical performance tasks showing an average of 35.76 meters longer distance in 6-minute walking ($p=0.001$) and an average of 1.1 seconds shorter star-climbing time ($p<0.001$) compared to the subjects in attention control group.

In conclusion, the positive effects of Tai Ji on balance control, muscle strength, and cardiovascular and respiratory function have been demonstrated by several previous studies. As one of the recommended knee OA nonpharmacologic treatments, Tai Ji has been shown to relieve pain and improve the quality of life for knee OA patients.

Biomechanics study of Tai Ji

Kinematics Studies

Lower extremity movements are the fundamental movements of Tai Ji exercise. Various movement patterns of Tai Ji are based on several basic foot movements (15). Mao et al. (28) classified the 42-form Tai Ji lower extremity movements into seven support patterns and six step directions. The support patterns included full double limb support, single-limb left support, single-limb right support, left support with right toe touch, left support with the heel touch, right support with left toe touch and right support with left heel touch. The six step direction categories are anterior movement, stepping backward, stepping sideways, up and down stepping,

stepping turning and fixed step. They videotaped the performance of sixteen subjects for the whole set of 42-form Tai Ji and analyzed the total duration, percentage duration and average duration of each support pattern and step direction. They demonstrated 68.15% longer duration in double-limb support and 55.34% lesser duration in single-limb support in Tai Ji movement than those in normal walking. Spending more time in double-limb support probably helped maintain balance control during movement. The practicing of single-limb support in Tai Ji may contribute to improved single-limb balance ability. They also discussed that stepping backward and stepping turning can be important strategies in preventing falls in elderly people. At last, their results showed although the duration of a step in each direction was short, changing directions was frequent and requires accurate control of balance, Thus, practicing changing directions was thought to be effective for reducing falls.

To continue investigating the characteristics of foot movements in 42-form Tai Ji, Mao et al. (27) selected five foot movements from six step direction categories and examined the plantar pressure distribution. The sole of the foot was divided into nine plantar regions, including medial and lateral heel, medial and lateral mid foot, 1st metatarsal head, 2nd-3rd metatarsal heads, 4th-5th metatarsal heads, big toe, and rest of toes. Big toe and first metatarsal head regions showed greater loading than other regions ($p<0.05$), which suggests greater anterior and medial plantar loading were needed to maintain balance during Tai Ji movements. Compared with normal walking, a larger center of pressure (CoP) displacement in the medial/lateral direction was found during Tai Ji movements. Furthermore, forward movement showed a greater displacement in the anterior/posterior direction than normal walking. They suggested that the larger displacement of the CoP in Tai Ji might cause the lower extremity to recruit more muscles to keep balance than normal walking. Thus, Tai Ji

should increase the lower extremity muscle strength and subsequently improve postural control.

Mao et al. (29) also investigated the plantar pressure distribution during Tai Ji single leg stance. Sixteen experienced Tai Ji practitioners performed an entire set of 42-form Tai Ji. The medial-lateral displacement of the CoP during single leg stance in Tai Ji was 15.6% greater than during normal walking ($p<0.05$). Since single leg stance is commonly involved in many daily activities, they suggested that practicing Tai Ji single leg stance movement might help stimulate the precise neuromuscular control in lower extremities and therefore improve single-limb balance.

Several previous biomechanical studies on Tai Ji analyzed different fundamental representative movements of Tai Ji. Xu, Li and Hong (54) investigated the kinematics and electromyographic (EMG) muscle activity of a representative Tai Ji movement, Brush Knees and Twist Steps (BKTS). Six Tai Ji masters participated in the study. They performed the BKTS three times while kinematic data and EMG activities of the rectus femoris, semitendinosus, gastrocnemius and anterior tibialis were collected. Although center of gravity changed frequently and continuously, the speed of motion was slow. Both knee and ankle joint had a large range of motion. According to EMG data, the lower extremity muscles frequently showed alternation in eccentric, concentric and static contractions. Thus they concluded BKTS required well-controlled muscle coordination. Repetitive practicing in this Tai Ji movement may be beneficial for balance control.

There are some biomechanical studies only focusing on a Tai Ji master's performance. Chan, Luk and Hong (7) recruited a Tai Ji master with 22 years of experience. A sequence of basic Tai Ji movements, shifting center of body's gravity backward and forward based on the lunge, that included ward off, roll back, press and

push was recorded. The three-dimensional joint angles of the hip, knee, ankle and trunk during the push movement were analyzed. They also performed EMG analysis on the lumbar erector spinae, the rectus femoris, medial hamstrings and medial gastrocnemius. During retracting components of the pushing movement, all the joints on the posterior support leg were flexed, while all the joints on the anterior leg were extended. When pushing forward, the change of each joint angle was opposite to the previous movement. The trunk kept an upright position during the entire movement. Eccentric muscle contraction occurred in the rectus femoris and the gastrocnemius during the retracting components of the movement. Results suggested the repeated weight shifting movement may benefit to strengthen the muscles of the lower extremities.

Chen et al. (10) examined the defense technique in Tai Ji Push Hands by comparing a Tai Ji master to 20 inexperienced subjects. The dependent variables included range of motion of lower extremities, ground reaction force, and EMG activitie of the rectus femoris, semitendinosus, and medial gastrocnemius muscles. The Push Hands included a slightly trunk rotation, knee extension in the posterior support leg. The Tai Ji master showed high EMG activity in rectus femoris muscles, which indicated he was using posterior leg support to resist the incoming attack. With a better defense technique, the Tai Ji master was able to defend all of the attacking movements, however the inexperienced subjects failed to make effective defense.

Wu et al. (52) performed a series of biomechanical studies on Tai Ji gait. In 2004, they compared kinematic variables and muscle action pattern between Tai Ji and normal gait. Ten subjects participated in the study, but only one of them had been practicing Tai Ji for 6 years. Others did not have any Tai Ji experience and they were asked to practice Tai Ji gait for only seven days prior to data collection. Both

temporal and spatial features were measured during Tai Ji and normal gait. The temporal features included the duration of initial foot contact, toe off and gait cycle. The spatial features included stride length, and joint position. In Tai Ji gait, the gait cycle duration and single stance duration were 10.6 seconds and 1.4 seconds longer than those in slow walking ($p<0.05$ for all comparisons). The stance/swing ratio was also 175% larger in Tai Ji compared to slow walking ($p<0.05$).. During Tai Ji gait, the body position showed a lateral shifting and 2% lower maximum shoulder height than normal gait. The greater range of motion in ankle dorsal and plantar flexion, knee flexion, hip flexion, and hip abduction caused higher muscle activity in tibialis anterior, rectus femoris and tensor fasciae latae muscles in Tai Ji gait. Moreover, those muscles were all activated for a longer proportion of the gait cycle than normal gait. The quantification of the Tai Ji gait provided comprehensive understanding of its benefits on balance control and muscle strengthening.

Wu (50) also compared Tai Ji gait between elderly (age: 72 ± 8 years) and young (age: 28 ± 6 years) adults. All subjects had at least four months of experiences in practicing Tai Ji. The dependent variables included spatial and temporal parameters and muscle EMG activity. The age related differences in Tai Ji focused on the height of posture, duration of single stance phase, and knee extensor activity. Elderly adults had 40% higher posture, 50% shorter single stance duration, 39% lower knee extensor muscle electromyographic activation and 24.3% shorter knee extensor muscle activation than the young adults ($p<0.016$ for all comparisons). The results indicated that elderly adults faced greater challenges in balance control than young adults due to less muscle strength.

Kinetic Studies

Wu and Hitt (51) compared GRF, center of pressure (CoP) and plantar pressure patterns during Tai Ji gait (0.088±0.05 m/s) to slow walking (0.84±0.15 m/s). Tai Ji gait showed greater peak medial GRF (12 ± 2% Body Weight (BW)) than walking during the first double stance phase (p=0.01). They also found Tai Ji gait had an average of 62.5% lower loading rate in all three dimensions through the entire gait cycle than walking (p<0.001). During second double stance phase, Tai Ji gait had significantly less plantar pressure difference between forefoot and rearfoot then walking (p<0.001). Moreover, contact area reached peak values three times during Tai Ji gait in three stance phases which were first double stance, single stance and second double stance phase, whereas it only reached peak value once in single stance phase during walking. Range of CoP displacements were 42.2% and 7% larger in medial-lateral and anterior-posterior directions respectively in Tai Ji gait compared to slow walking (p<0.05). These results indicated that during Tai Ji gait, body weight is evenly distributed between forefoot and rearfoot.

Wu and Millon (53) compared the age differences in lower extremity joint kinetics during Tai Ji gait and normal walking. Two groups of healthy subjects were recruited; young adults between 18 and 30 years of age and elderly adults over 60 years of age. The inverse dynamic approach was used to calculate joint reaction force and moments. During Tai Ji gait, the ankle showed a significantly smaller peak plantar flexor moment compared to the normal gait. Both knee and hip demonstrated greater peak moment in frontal and transverse plane movements than normal gait. During the transition from double stance to single stance, the peak knee extensor moment and peak external adductor moment were 100% and 90% greater respectively in Tai Ji gait than during the normal gait (p<0.025) respectively,. Knee OA patients

also had similar gait characteristic in that the greater external adductor moment was found during single stance phase of walking compared to healthy subjects (2, 17, 59).

Wong et al. (49) investigated the biomechanics of push-hand exercises. The dependent variables included GRF and plantar force distribution during push hand with or without an opponent. The results indicated that the vertical GRF generated by push-hand exercises (103 ± 1.4% BW) is smaller than that during walking and Tai Ji gait. Moreover, toe area sustained the greatest plantar pressure among the nine plantar areas during push hand. Thus, push-hand may be a good balance-training tool for older people and for those with arthritis.

In conclusion, longer gait cycle duration and greater range of motion of lower extremity joints were found for Tai Ji gait. Anterior and medial plantar regions showed greater loading than other regions in Tai Ji gait. The mediolateral displacement of CoP was greater in Tai Ji gait compared with normal walking due to the needs of balance control. The kinetic results showed that the ankle had smaller peak plantar flexor moment and knee had greater peak extensor moment and peak external adductor moment in Tai Ji gait than normal gait.

Chapter III

Participants and Methods

Participants

Seventeen active and healthy young adults between the ages of 18 to 30 years were recruited for the biomechanics study (age: 23.9±2.7 years, height: 1.73 ± 0.08 m, body mass: 69.0 ± 13.0 kg, BMI: 22.8 ± 3.9). Tai Ji experience was not required. For the subjects without any Tai Ji experience, a Tai Ji master taught them selected Tai Ji movements and practiced those movements for at least two week before data collection. Participants were free from injury within past six months and should not have had major lower extremity and low back injuries. Participants were recruited from the University of Tennessee Knoxville campus and surrounding community using flyers posted at the Tennessee Recreational Center for Students and residence, email announcements to the UT community, and making announcements in courses offered by the Physical Education Activity Program. Participants provided written informed consent approved by the University of Tennessee Institutional Review Board prior to data collection.

The number of subjects was determined by sample size analysis software, (3.1, G*Power) (37). Because of a lack of similar previous studies, we choose to use 0.25, a medium effect size defined by Cohen (37), to estimate the sample size. A sample size of 15 was estimated in power analysis with an alpha level of 0.05, a sample power of 0.8 and effect size of 0.25.

Equipment

Participants wore a pair of standard lab shoes. For 3D kinematic data collection, a nine-camera infrared motion capture system (120 Hz, Vicon Motion

Analysis, Inc., Oxford, UK) was used. Anatomical reflective markers were placed bilaterally on the acromion process, iliac crest, greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, 1^{st} and 5^{th} metatarsal heads and toes. Tracking reflective markers were placed on a semi-rigid thermoplastic shell with four tracking markers on the trunk, pelvis, thigh, and shank. Three tracking markers were attached to the medial, lateral and posterior heel counter of the shoe. After precisely placing all the markers, a single static trial was recorded. Once the static trial was correctly labeled, the anatomical markers were removed before collecting dynamic movement trials.

Three force platforms (1200 Hz, Advanced Mechanical Technology, Inc., Watertown, MA USA) were used to measure the GRFs and lower extremity joints moments. First and second force platform were placed close to each other, the third force platform was placed in front of the first force platform. The 3-D kinematic and force platform data were collected simultaneously using the Nexus software of the Vicon system.

Testing protocol

The testing took approximately 2 hours. At the beginning of the session, the subject was asked to sign the informed consent form and to fill out a survey about their demographic information including Tai Ji experience and injury history and a Physical Activity Readiness Questionnaire (PAR-Q) form. After that, subject's height and mass were measured. In addition, the subjects were asked to complete a self-directed 10-minute warm up, including five minutes of stretching of major lower extremity muscles and five minutes of practicing our selected Tai Ji movements on the force platforms.

The subject first performed five walking trials at 0.8 m/s (±5%) (51) . The walking speed was monitored by a pair of photocells (63501 IR, Lafayette Instrument Inc., IN, USA) placed at shoulder height and 3 meters far from each other across the force platform. A successful trial was when the subject made proper contact with the force platform with right foot. The subject was then asked to perform three trials in each of eight movement conditions: lunge, push down, and kick with each performed at high and low poses, and two different pseudo steps (one with toe touch on the ground and another with heel touch on the ground). The high pose was defined as a maximum knee flexion angle of 35 ± 5°, while the low pose was defined as 80 ± 5° of the support leg for first two movements. For kick, the high pose referred to a kick to a height at a knee level, while the low pose referred to a kick to a height at hip level. Maximum knee flexion angle was monitored by using an electrogoniometer placed on the lateral side of the right knee. The speed of Tai Ji movements was controlled by a metronome at pace of 40 beats per minute that was similar to walking speed. The subjects were given up to five minutes rest between trials. The movement conditions were randomized first and followed by the randomization of high- and low-poses.

Data and statistical analysis

3D kinematic and kinetic variables of the lower extremity joints were computed using Visual 3D software suite (C-Motion, Inc.). Kinematic and GRF data were smoothed at cutoff frequencies of 4 and 50 Hz, respectively, using a fourth-order zero-lag Butterworth low-pass filter. An X-y-z Cardan sequence was used in the 3D joint angle computation. The right-handed rule was used to determine positive and negative signs of the joint angles. Positive values indicated knee extension angle and extensor moment, knee adduction angle and adductor moment, and knee internal rotation angle and internal rotation moment. The dependent variables included peak

vertical GRF, peak knee flexion angle, knee joint ROM, and peak knee joint moment. Peak angles, and moments were determined using a customized program (VB_V3D, MS Visual BASIC) and selected variables were further organized for statistical analysis and reports using another customized program (VB_Table, MS Visual BASIC). The GRFs and joint moments were normalized to the participant's body weight and mass, respectively, yielding units of BW and Nm/kg. Because there were no significant differences of most of examined variables between toe-touch and heel-touch pseudo-steps and the toe-touch pseudo-step appears much more often (8 times) in 42-form style Tai Ji than times the heel-touch pseudo-step (2 times), we decided to include only toe-touch pseudo-step for further analyses.

A 3 ×2 (movement × pose) repeated measures analysis of variance (ANOVA) was used to examine effects of the lunge, pushdown and kick movements on the selected dependent variables (IBM SPSS Statistics 22, Chicago, IL). Pair-sample t-tests were performed in the post hoc analysis with Bonferroni adjustments to determine differences among the three movements, and high- and low-poses. Additionally, two separate one-way ANOVAs were performed to compare differences of the high-pose movements and low-pose movements with pseudo-step and walking, respectively. Post hoc comparisons using paired-samples t-tests were used to determine differences between high- and low- pose. An alpha level of 0.05 was set a priori.

Chapter IV

Knee Biomechanical Characteristics of Selected Knee Unfriendly Movements in 42-form Tai Ji

ABSTRACT

Tai Ji is one of the recommended non-pharmacologic treatments for knee osteoarthritis (OA), but it is not clear if all Tai Ji movements would be suitable and beneficial for knee OA patients. The purpose of this study was to examine 1) GRF and knee kinematic and kinetic characteristics of the selected knee unfriendly Tai Ji movements, 2) effects of high- and low-pose of these movements on those characteristics, and 3) compare biomechanical variables between the Tai Ji movements and slow waking. Seventeen subjects participated in this study. They performed eight movement conditions: slow walking, high and low lunges, high and low pushdown, high and low kick and toe-touched pseudo-step. The peak knee extensor moment was 67.3%, 94.0% and 97.9% greater in the low-pose lunge, pushdown and kick than those of high-pose movements ($p<0.001$ for all comparisons). The high-pose also caused a reduced peak knee abduction moment ($p=0.004$) and knee adduction ROM in lunge ($p<0.001$). Greater peak knee extensor moments were found in all Tai Ji movements of both poses, except for high pose kick, compared to slow walking ($p<0.001$). Based on the results, the high-pose position would be more suitable for Tai Ji participants with knee OA than low-pose. Further study may be needed to demonstrate effects of high-pose Tai Ji training in managing pain and physical functions of knee OA patients.

Keywords: Tai Ji, knee OA, knee joint moment, knee ROM, slow walking

INTRODUCTION

It has been reported that 46% of U.S. adults suffer from painful knee osteoarthritis (OA) in at least one leg by 85 years of age (31). Knee OA symptoms greatly limit a patients' ability to perform daily tasks such as standing up, walking and running, and star ascent and descent. The recommended treatment for knee OA by the American College of Rheumatology include a combination of non-pharmacologic and pharmacologic therapies intended to improve physical function, manage pain and improve quality of life (14). Tai Ji has also been recommended as one of non-pharmacologic treatments among others such as assistive devices and acupuncture (41).

Tai Ji, as a mind-body therapy, is a traditional Chinese martial art that includes natural postures, and gentle and smooth movement. It has become a popular activity around the world regardless of age, gender, or race. In recent years, Tai Ji has been shown to relieve pain and improve the quality of life for knee OA patients (6, 23, 40). Most of Tai Ji training programs have shown improvements in the Western Ontario and MacMaster Universities Osteoarthritis Index (WOMAC) (5, 16) and visual analog scale (VAS) (16) for pain (6, 33, 40, 47). However, insufficient training and excessive knee flexion have been reported to cause knee pain in Tai Ji participants (60). It has been shown that 37.5% of participants without previous pain prior to Tai Ji training experienced knee pain after practicing Tai Ji. The number of elite Tai Ji participants (n=15) who reported knee pain was less than that of beginners (n=253) with 55.9% of participants reporting knee pain during squatting and 92.9% who kept knee flexion angle greater than 135° experienced knee pain. Knee flexion angle, which is associated with the pose height, deserves greater attention when practicing Tai Ji, especially for participants who experienced knee pain before practicing Tai Ji.

However, the effect of pose height on knee biomechanical characteristics is currently unknown in the literature.

It is also not clear if all Tai Ji movements would be suitable and beneficial for knee OA patients. Furthermore, it is unknown if Tai Ji movements place similar or higher loads to the knee joint during Tai Ji movements compared to other common daily activities, e.g., walking and stair ambulation. Although several biomechanical studies have been conducted on both kinematic and kinetic characteristics of Tai Ji gait and kinematics of some support patterns, no biomechanical data are available in the literature on the majority of Tai Ji movements.

Lower extremity movements are the fundamental movements of Tai Ji exercises. Mao et al. (28) classified the 42-form Tai Ji lower extremities movements into seven support patterns and six step directions. Each basic foot movements showed different durations and plantar pressure distribution patterns from the others (27). Among the Tai Ji movements, full double-limb support, single-limb support and pseudo-step represented 33.6%, 35.7% and 30.6% of the total duration, respectively. Five fundamental Tai Ji step direction distribution (Moving forward, backward, sideways, up-down and fixing to the ground) showed smaller GRF magnitude and different characteristics of GRF curves than those in normal walking (27).

In order to identify knee unfriendly movements of the 42-form Tai Ji, the competition form of Tai Ji, the support patterns from a previous study (28) were modified and placed into six fundamental movement categories: lunge, step, support, foot rotation, body weight shifting and trunk rotation (Appendix B, Table 4). There were four direction subcategories, forward, backward, sideway and diagonal for the lunge and step. The support was also divided into three subcategories, single-leg support, double-leg support, and pseudo-support. After analyzing 42-form movements

performed by Tai Ji experts (24, 48), five most common fundamental movements were identified, forward lunge, lateral lunge, pseudo-step, horse stance, and single leg support. Movements including multiple knee flexions and long duration were selected as knee unfriendly movements that included forward lunge, pushdown (lateral lunge), kick (single leg support) and pseudo-step (Appendix B, Table 5).

In a previous studies, it was shown that greater knee flexion range of motion (ROM) in Tai Ji gait caused higher muscle activity in rectus femoris (52) compared to normal gait. In Tai Ji movements of Brush Knees and Twist Steps, the rectus femoris muscle also showed higher muscle activity level than that in semitendinosus(54). When comparing Tai Ji gait between elderly adults (age range: 61-85 years) and young adults (age range: 21-45 years), smaller knee extensor muscle activity was found in the elderly adults (50). During the transition from double stance to single stance in Tai Ji gait, , , the knee extensor moment and abduction moment were approximately 100% and 90% greater than those in slow walking respectively (53).

Besides the Tai Ji gait, very few studies have examined knee joint kinetics of Tai Ji movements (50, 51, 53, 54). It is unknown if certain Tai Ji movements impose greater loading to knee joint than others. Furthermore, it is common to practice Tai Ji movements in low center of gravity (COG) position with rather large knee flexion. The low-pose may place increased load to knee joint when practicing Tai Ji. Therefore, it is especially important to understand biomechanical characteristics related to knee joint loading in Tai Ji movements perceived as knee “unfriendly” and effects of low- and high- poses on knee joint loading. This information is important to provide guidelines for the patient populations such as knee OA who want to practice Tai Ji. Therefore, the purpose of this study was to examine 1) GRF and knee kinematic and kinetic characteristics of the identified knee unfriendly Tai Ji

movement patterns, 2) effects of high- and low-pose of these movements on those characteristics, and 3) compare biomechanical variables between the Tai Ji movements and slow waking. It was hypothesized that the peak knee extensor moment would be smaller in four high-pose knee unfriendly Tai Ji movements than the respective low-pose movements and that the peak knee extensor moment would be greater in the Tai Ji movements compared to low speed walking.

METHODS

Participants

Ten healthy male and seven female subjects (age: 23.9 ± 2.7years, height: 1.73 ± 0.08 m, body mass: 69.0 ± 13.0 kg, BMI: 22.8 ± 3.0) volunteered for participation in this study. The subjects were recruited from local Tai Ji club, the Tai Ji class of the university, and using the flyers posted at UT community. For the subjects without any Tai Ji experience, a Tai Ji master taught them the selected Tai Ji movements and practiced those movements for one hour per session, two sessions per week for at least two weeks before data collection. For the subject who had the Tai Ji experience, they were asked to watch the video performed by a Tai Ji expert and reviewed the selected movements before the data collection. Participants were free from injury within past six months and did not have had major lower extremity and low back injuries. Each subject gave informed consent and the study was approved by the Institutional Review Board.

For three dimensional (3D) kinematic data collection, a nine-camera infrared motion capture system (120 Hz, Vicon Motion Analysis, Inc., Oxford, UK) was used. Anatomical reflective markers were placed bilaterally on the acromion process, iliac crest, greater trochanter, medial and lateral femoral epicondyles, medial and lateral malleoli, 1st and 5th metatarsal heads and toes. Tracking reflective markers were

placed on a semi-rigid thermoplastic shell with four tracking markers on the trunk, pelvis, thighs, and shanks, and with three tracking markers for shoes placed on the posterior heel counter of standard lab shoes (Noveto, Addidas). Three force platforms (1200Hz, Advanced Mechanical Technology, Inc., USA) were used to collect ground reaction forces (GRF) and joint moments. The 3D kinematic data and GRF data were collected simultaneously using Vicon Nexus software.

Experimental Protocol

Upon arrival to the laboratory, the subject was asked to complete a self-directed 10-minute warm up, including 5 minutes of stretching of major lower extremity muscles and 5 minutes of practicing the selected Tai Ji movements on the force platforms. The subject first performed three walking trials at speed of 0.8 m/s (±5%) (51) . The walking speed was monitored by a pair of photocells (63501 IR, Lafayette Instrument Inc., IN, USA) placed at shoulder height and 3 m apart across the force platform. A successful trial was a trial that the subject made proper contact with the force platform with right foot. Then the subject was asked to perform three trials in each of eight movement conditions: lunge, pushdown, and kick performed at high- and low-poses, and pseudo-step performed with toe and heel on touch the ground. The high-pose was defined as the maximum knee flexion angle of 35 ± 5° while the low-pose was defined as 80 ± 5° of the support leg for lunge and pushdown. For kick, the high pose referred to the kick to a height to the knee level while the low-pose referred to the kick to a height to the hip level. Maximum knee flexion angle was monitored by using an electrogoniometer (Biometrics Inc.) placed on the lateral side of the right knee joint. The speed of Tai Ji movements was controlled by a metronome at pace of 40 beat per minute that was average foot strikes per minutes during slow walking. The subjects were given as much rest as needed between trials. The four Tai

Ji movements were randomized first and followed by the randomization of high- and low-poses of each movement.

Data and Statistical Analysis

Visual 3D (C-Motion Inc.) was used to compute 3D kinematics and kinetics. Kinematic and GRF data were smoothed at cutoff frequencies of 4 and 50 Hz, respectively, using a fourth-order zero-lag Butterworth low-pass filter. An X-y-z Cardan sequence was used in the 3D joint angle computation. The right-handed rule was used to determine positive and negative signs of the joint angles. Positive values indicated knee extension angle and extensor moment, knee adduction angle and adductor moment, and knee internal rotation angle and internal rotation moment.

Peak angles, and moments were determined using a customized program (VB_V3D, MS Visual BASIC) and selected variables were further organized for statistical analysis and reports using another customized program (VB_Table, MS Visual BASIC). The GRFs and joint moments were normalized to the participant's body weight and mass, respectively, yielding units of N/kg and Nm/kg. Because there were no significant differences of most of examined variables between toe-touch and heel-touch pseudo-steps and the toe-touch pseudo-step appears much more often (8 times) in 42-form style Tai Ji than times the heel-touch pseudo-step (2 times), we decided to include only toe- touch pseudo-step for further analyses.

A 3 ×2 (movement × pose) repeated measures analysis of variance (ANOVA) was used to examine effects of the lunge, pushdown and kick movements on the selected dependent variables (IBM SPSS Statistics 22, Chicago, IL). Pair-sample t-tests were performed in the post hoc analysis with Bonferroni adjustments to determine differences among the three movements, and high- and low-poses. Additionally, two separate one-way ANOVA were performed to compare differences

of the high-pose movements and low-pose movements with pseudo-step and walking, respectively. Post hoc comparisons using paired-samples t-tests were used to determine movement differences. An alpha level of 0.05 was set a priori.

RESULTS

Comparisons of high and low pose of Tai Ji movements

A significant movement by pose interaction was found for knee peak flexion angle ($p<0.001$, Table 1). Post hoc comparisons showed that it was smaller for high and low kicks than both lunges ($p<0.001$ & $p<0.001$) and pushdowns ($p<0.001$ & $p<0.001$), respectively (Table 1). It was greater in the low pose lunge, pushdown and kick than those of respective high pose movements ($p<0.001$, $p<0.001$ & $p<0.001$, respectively). A significant movement by pose interaction was found for knee flexion ROM ($p<0.001$). The ROM of high and low kicks was smaller than both lunges ($p<0.001$ & $p<0.001$) and pushdowns ($p=0.005$ & $p<0.001$), respectively. It was greater in low pose lunge, pushdown and kick compared to respective high pose movements ($p<0.001$, $p<0.001$, & $p<0.001$).

There was a significant movement by pose interaction for knee adduction ROM ($p<0.001$). The ROM of high and low kicks was smaller than both lunges ($p<0.001$ & $p<0.001$) and pushdowns ($p=0.004$ & $p=0.001$), respectively. It was greater in low pose lunge ($p<0.001$) and pushdown ($p<0.001$) than respective high pose movements. A significant movement by pose interaction was found for knee external rotation ROM ($p<0.001$). Post hoc comparisons showed that the ROM of high and low kicks was lower than both lunges ($p<0.001$ & $p<0.001$), and pushdowns ($p<0.001$ & $p=0.006$). Low lunge showed greater knee external rotation ROM than high lunge ($p=0.022$), but high pushdown showed greater knee external rotation ROM than low pushdown ($p=0.004$).

The peak vertical GRFs were greater in low pose lunge (p=0.006), pushdown (p=0.036) and kick (p=0.019) than those of high pose movements (Table 2). There was a significant movement by pose interaction for peak knee extensor moment (p<0.001). It was smaller for high and low kicks than both lunges (p<0.001 & p<0.001) and pushdowns (p<0.001 & p<0.001). Additionally, it was greater in the low pose lunge, pushdown and kick than those of high pose movements (p<0.001, p<0.001 & p<0.001, respectively). A significant movement by pose interaction was observed for peak knee abduction moment (P<0.001). It was greater for high and low lunges than both pushdowns (p=0.045 & p=0.019) and kicks (p=0.009 & p=0.002). It was greater in low lunge than high lunge (p=0.004).

A significant movement by pose interaction was found for peak knee internal rotation moment (p<0.001). It was smaller for both kicks than both lunges (p=0.004 & p<0.001) and pushdown (p=0.04 & p=0.003), respectively. Moreover, it was greater in low pose of lunge, pushdown and kick than respective high pose movements (p<0.001, p<0.001 & p=0.001).

Comparisons between Tai Ji movements and walking

Post hoc comparison results showed that peak knee flexion was smaller for high lunge and pushdown than pseudo-step (p<0.001 & p<0.001) and walking (p< 0.001& p<0.001) whereas it was greater for low lunge and pushdown than pseudo-step (p<0.001 & p<0.001) and walking (p <0.001 & p<0.001, Table 1). In addition, it was smaller for both kicks compared to pseudo-step (p<0.001) and walking (p<0.002) whereas it was greater in pseudo-step than walking (p = 0.039). Knee flexion ROM for high lunge, high pushdown and both kicks was smaller than pseudo-step (p<0.018 for all comparisons) and walking (p<0.001 for all comparisons, Table 1). However, it

was greater for low lunge and pushdown than pseudo-step ($p<0.001$ & $p<0.001$) and walking ($p<0.001$& $p<0.001$).

Knee adduction ROM for pseudo-step was greater than both pushdowns ($p<0.001$ & $p=0.008$) and kicks ($p<0.001$ & $p<0.001$); but it was smaller than low lunge ($p=0.002$). Additionally, knee adduction ROM was smaller for walking than both lunges ($p<0.001$ & $p<0.001$), pushdowns ($p<0.001$ & $p<0.001$), and pseudo-step ($p<0.001$), respectively.

Peak vertical GRF was greater for both kicks ($p<0.001$ & $p<0.001$) than walking (Table 2). Peak knee extensor moments were smaller for high lunge, high pushdown and both kicks than pseudo-step ($p<0.001$ for all comparisons), but greater than walking ($p<0.001$ for all comparisons, Table 2). It was greater for low pushdown than pseudo-step ($p<0.004$). Peak knee abduction moments were greater for pseudo-step than pushdowns ($p<0.001$ & $p=0.027$), kicks ($p<0.001$ & $p<0.001$), and walking ($p<0.001$). Peak knee internal rotation moments were smaller for high lunge and pushdown and both kicks than pseudo-step ($p<0.001$ for all comparisons), whereas low lunge was greater than pseudo-step ($p=0.026$). It was smaller for walking than both lunges ($p<0.001$ & $p<0.001$) and pushdowns ($p=0.001$ & $p<0.001$), and pseudo-step ($p<0.001$).

DISCUSSION

Comparisons of high- and low-pose Tai Ji movements

The purpose of this study was to examine GRF and knee kinematic and kinetic characteristics of four selected knee unfriendly movements that are commonly used in 42-form Tai Ji and effects of high- and low-pose on GRF and knee kinematic and kinetic movements on those characteristics. The first hypothesis was that the high-pose movements would show smaller peak knee extensor moment than the respective

low-pose movements.

Our first hypothesis was partially supported by our results, which showed that peak knee extensor moment was greater in the low-pose lunge, pushdown and kick than those of high-pose movements. Previous studies have only investigated biomechanical characteristics of Tai Ji gait, and no GRF, and knee kinematics and kinetics have been investigated for other fundamental Tai Ji movements. Therefore effects of different pose heights of Tai Ji movements on knee joint kinematics and kinetics were unknown in literature. The peak GRF was smaller in high-pose lunge, pushdown and kick than those of low-pose movements. Although the increases were small (0.22 BW on average), these results suggest that the overall external load to the body during the low-pose movements were slightly greater than the high-pose movements. The four movements we studied were chosen from 42-form Tai Ji (Yang style) and are also common in other Tai Ji styles (e.g., Chen, Sun and Wu style). Peak knee flexion angles were 38.5°, 38.6° and 23.8° for high- pose lunge, pushdown and kick respectively, which were 53.6%, 55.0% and 35.1% less than the respective low-pose movements. Knee flexion ROMs were also 58.9%, 64.7% and 51.4% less in high-pose lunge, pushdown and kick compared to respective low-pose movements. In order to perform these movements at the low-pose positions with more flexed knee angles, the knee extensors contracted harder to increase their moment outputs, which was partially reflected in the increased vertical GRFs.

The high-pose caused a reduced peak knee abduction moment during the lunge. Peak knee abduction moment was 0.54 Nm/kg for high-pose lunge, which was 22.9% less than low-pose lunge. Knee adduction ROM was also 49.4% smaller in high-pose lunge compared to low-pose lunge. It has been reported that increased knee adduction angle is related to increased abduction moment due to increased frontal

plane GRF moment arm about the knee in walking (4) and stair decent (34). Excessive knee abduction moment has been linked to medial compartment knee OA in numerous studies (2, 3, 17, 58). When people with medial knee OA want to practice Tai Ji movements that often contain lunges, these movements were recommended to be performed at a high-pose position with a knee angle around 40 degrees to minimize both knee extensor and abduction moments.

In addition to the reduction of sagittal and frontal plane moments, high-poses also caused reduced peak internal rotation moment in lunge and pushdown. Peak knee internal rotation moments were 0.25 and 0.21 Nm/kg for high-pose lunge and pushdown, which were 51.9% and 41.7% less than those in low-pose lunge and pushdown, respectively. Knee external rotation ROM was 20% less in high lunge compare with low lunge. However, the low-pose pushdown demonstrated lower peak external rotational ROM than the high-pose pushdown. When the knee is kept at a more flexed position, it was harder to rotate at the same time.

Comparisons between Tai Ji movements and Walking

The second hypothesis was that the peak knee extensor moment would be greater in the four Tai Ji movements compared to a slow walking speed. The results showed greater peak knee extensor moments in all Tai Ji movements of both poses compared to walking, except for high-pose kick; therefore providing support for the hypothesis. The peak knee extensor moment was 173%, 165% and 284% greater in high-pose lunge, pushdown, and pseudo-step, respectively, compared to slow walking. In addition, high-pose lunge and pushdown had 24.0% and 23.9% lower peak knee flexion angle than slow walking. Wu (50) reported that Tai Ji gait had a 139% greater knee flexion ROM than slow walking. In our study, the walking speed was 0.8m/s, 38% slower than normal walking speed of 1.3m/s commonly found in

literature (46). When Tai Ji movements were compared with normal walking, the peak knee extensor moment was 36.8% and 32.9% higher in high-pose lunge and pushdown, respectively (46). However, the increases were even greater at 128%, 158% and 92.1% for low lunge, pushdown and pseudo-step, respectively, compared to normal walking (46).

Our extensor moment results support those of Wu et al. (53) who reported approximately 100% greater peak knee extensor moment during Tai Ji gait than walking. Tai Ji gait is an isolated leg movement from regular Tai Ji and is commonly involved in all styles of Tai Ji (52). It is similar to normal gait with both legs alternating between strides but with more flexed knee and hip during the swing phase (52). EMG data in previous literature also provided supporting evidence (50, 52, 54). For example, the rectus femoris muscle is more heavily recruited during Tai Ji gait for a longer proportion of the gait cycle compared to slow walking (52). To perform the selected movements and other related movements in Tai Ji, participants are required to exert greater extensor muscle strength for longer periods of time as the knee is kept in a more flexed position for most of time.

The current study showed no significant difference in peak vertical GRF between most of the Tai Ji movements and slow walking. But peak vertical GRF was 0.05 BW smaller in Tai Ji movements when compared with normal walking (46). Our findings were similar to the results of Wu's study (51). The authors reported that the peak vertical GRF was 1.09 BW for Tai JI Gait. Furthermore, five fundamental Tai Ji support patterns (Moving forward, backward, sideways, up-down and fixing to the ground) had smaller GRF magnitude and different shapes of GRF compared to normal walking (27). Thus, Tai Ji has a lower external loading than normal walking.

In the current study, knee abduction moment was 20% greater in high lunge

compared with slowing walking and was similar compared to that in normal walking (46). However, the peak knee abduction moments were even greater at 55.6% and 35.6% for low lunge and pseudo-step, respectively, compared to slow walking. Wu et al. (53) showed that the knee abduction moment was 90% greater during Tai Ji gait compared to slow walking. The peak internal rotation moment was on average 110% greater for all of the high-pose Tai Ji movements except for kicks compared to walking.

Comparisons between Tai Ji Movements

The peak knee extensor moment for high-pose kick were on average 113% less than high lunge and pushdown, and low kick was 94% on average lower than low lunge and pushdown. Since the kicks were performed in a much more extended knee position compared to the lunges, pushdowns and pseudo-step, the knee loading of kicks should lower than that of other movements. Knee joint loading is relatively higher in lunge, pushdown and pseudo-step as knee extensors are more heavily involved in maintaining more flexed knee postures. The previous study of Tai Chi gait (52) demonstrated knee extensor muscle had a significant higher activity level than flexor muscle. Xu et al. (54) reported higher rectus femoris muscle activity level than that in semitendinosus in Brush Knees and Twist Steps (BKTS), popular Tai Ji movements which contains lunges.

In the frontal plane, high- and low-pose lunge and pseudo-step had, on average, 40% greater peak knee abduction moment and 221% greater knee adduction ROM than the other Tai Ji movements. It has been reported that during walking an increased knee adduction angle causes increased frontal plane GRF moment arm and therefore the knee abduction moment increased (4). It has also been reported that the peak knee abduction moment for stair descent (0.77 Nm/kg) (34) was slightly greater

than lunge. If Tai Ji participants have medial knee OA, they are highly recommended to practice Tai Ji movements at a high-pose position, especially for those movements with a lunge.

Clinical application of the results

Our results of peak knee angle, extensor and abduction moment suggest that it is possible to reduce the peak knee moments if the knee joint is kept at a high pose (with a small flexion angle) when performing lunge, pushdown and kick in Tai Ji. Since knee abduction moment was closely related to medial knee OA, it is more suitable for Tai Ji participants with knee OA to practice at a high-pose position. Furthermore, increased knee internal rotation moments could cause twisting and overstretching of knee ligaments and other knee structures, therefore increased shearing stresses. We recommended the Tai Ji participants direct their knee and toe in the same direction to reduce the internal rotation moment and shear loading to knee joint.

Various styles of Tai Ji have been developed over several hundreds of years and major styles include Chen, Wu, Sun and Yang styles. Dr. Paul Lam, a family physician in Australia, led a team of Tai Ji and medical expert created a Tai Ji for arthritis program based on Sun style which was endorsed by the Arthritis Foundation of Australia and the U.S. Arthritis Foundation (9). Although there is no biomechanics study about the arthritis specific Tai Ji program, the peak knee flexion angle and ROM in Dr. Lam's performance (20) were significantly smaller than those in the standard 42-form Tai Ji (24, 48). Unlike Sun and Yang style, one of the outstanding features of Chen style Tai Ji is to keep at a low-pose during practice (20). Based on the result from this study, Chen style should not be recommended for knee OA patients.

During a deep squat, the meniscus and tibial and femoral articular cartilage are under increased stress at high flexion angles (39). The repeated compressive forces in deep flexion could influence the rate of degenerative changes to the knee over time in individuals who frequently perform activities in deep flexion (32), which could exacerbate knee osteoarthritis. The maximum knee flexion angle in OA patient was approximately 90° in a deep squat, and the angle decreases with increasing severity of OA (19). Knee OA patients are recommended to practice Tai Ji in a high pose with a knee flexion angle less than 90°. However, some of Tai Ji intervention studies (9, 11, 13, 33, 45) did not specify pose height, thus effects of high-pose Tai Ji training in managing pain and physical functions of knee OA patients are still largely unknown and warrant further investigations.

There are a few limitations in this study. At the time of subject recruitment, two subjects had been practicing for seven years. All other subjects had less than 2 month but at least 2 weeks to practice the selected movements prior to data collection. Furthermore, they were taught by different instructors. The effects of duration of practice on Tai Ji performance were unknown. Also, some subjects could not consistently reach the targeted peak knee flexion angle (75°-85°). But they were encouraged to flex the knee as much as they could.

Conclusions

The findings of this study indicate that peak knee extensor moment was greater in the low-pose lunge, pushdown and kick than those of high-pose movements. The high-pose also caused reduced peak knee abduction moment and knee adduction ROM in lunge. We found greater peak knee extensor moments in most of Tai Ji movements compared to slow walking. Kick showed smallest knee extensor moment compared with other Tai Ji movements, and lunge and pseudo-step

showed greater peak abduction moment than others. Based on the results of this study, Tai Ji participants with knee OA should practice at a high-pose position. Further study may be needed to demonstrate effects of high-pose Tai Ji training in managing pain and physical functions of knee OA patients.

Table 1. Peak knee angle and knee range of motion (ROM) of four Tai Ji movements and slow walking (deg): Mean ± SD.

		Lunge	Pushdown	Kick	Pseudo-Step	Walking
Peak Flexion[12*]	High	-38.5±7.6[bcd]	-38.6±6.8[bcd]	-23.8±12.6[cd]	-57.3±10.7[d]	-50.7±7.1
	Low	-83.0±8.5[bcd#]	-85.7±7.8[bcd#]	-36.7±11.7[cd#]		
Flexion ROM[12*]	High	-29.5±6.0[bcd]	-24.3±8.8[bcd]	-11.1±5.8[cd]	-45.0±13.0	-47.8±7.0
	Low	-71.7±8.7[bcd#]	-68.8±11.8[bcd#]	-22.4±10.2[cd#]		
Adduction ROM[12*]	High	13.2±3.6[abd]	7.1±2.9[bcd]	2.7±2.1[c]	16.48±4.5[d]	1.8±1.4
	Low	26.1±6.9[abcd#]	10.8±4.9[bcd#]	3.1±3.4[c]		
External Rotation ROM[12*]	High	-12.8±5.1[b]	-19.7±7.1[bc]	-3.8±3.0[c]	-12.9±7.8	—
	Low	-16.0±6.4[b#]	-13.8±9.7[b#]	-3.6±4.7[cd]		

[1] – significant movement main effect, [2] – significant pose main effect, * – significant movement x pose interaction, [a] - significant difference from Push Down, [b] - significant difference from Kick, [c] - significantly different from Pseudo Step (Toe), [d]- significantly different from walking, [#]- significantly different from high-pose of same movement, "—" – no comparable values are available.

Table 2. Peak GRF (BW) and knee joint moments (Nm/kg) of four Tai Ji movements and slow walking: Mean ± SD.

		Lunge	Pushdown	Kick	Pseudo-step	Walking
Vertical GRF[2]	High	1.05±0.07	1.05±0.08	1.08±0.07[d]	1.06±0.07	1.06±0.08
	Low	1.08±0.08[#]	1.07±0.09[#]	1.09±0.07[d#]		
Peak extensor moment[12*]	High	1.04±0.21[bcd]	1.01±0.28[bcd]	0.48±0.41[c]	1.46±0.26[#]	0.38±0.19
	Low	1.74±0.36[bd#]	1.96±0.51[bcd#]	0.95±0.47[cd#]		
Peak abduction moment[12*]	High	-0.54±0.10[abd]	-0.43±0.14[cd]	-0.44±0.13[c]	-0.61±0.16[#]	-0.45±0.10
	Low	-0.70±0.23[abd#]	-0.46±0.17[c]	-0.43±0.15[c]		
Peak Internal Rotation Moment[12*]	High	0.25±0.07[bcd]	0.21±0.06[bcd]	0.13±0.10[c]	0.40±0.08[#]	0.11±0.06
	Low	0.52±0.13[abcd#]	0.36±0.15[bd#]	0.19±0.10[c#]		

[1] – significant movement main effect, [2] – significant pose main effect, * – significant movement x pose interaction, [a] - significant difference from Push Down, [b] - significant difference from Kick, [c] - significantly different from Pseudo Step (Toe), [d] - significantly different from walking, #- significantly different from high-pose of same movement.

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APPENDICES

APPENDIX A: INDIVIDUAL SUBJECT CHARACTERISTICS

Table 3. Individual subject characteristics

Subject	Gender	Age (years)	Tai Ji Experience (months)	Height (m)	Weight (kg)	BMI (kg/m^2)
1	Female	25	84	1.64	61.9	23.0
2	Female	25	1	1.61	52.4	20.2
3	Male	23	0.5	1.79	88.7	27.7
4	Male	23	0.5	1.75	68.4	22.3
5	Female	28	96	1.65	56.0	20.6
6	Female	21	1.5	1.70	56.7	19.6
7	Female	21	3	1.70	60.5	20.9
8	Male	20	2	1.80	78.7	24.3
9	Male	26	1	1.80	64.4	19.9
10	Female	24	12	1.70	62.1	21.5
11	Male	22	1	1.83	86.2	25.7
12	Male	23	6	1.78	76.0	24.0
13	Male	27	0.5	1.75	90.9	29.7
14	Male	25	0.5	1.80	70.0	21.6
15	Female	25	1	1.58	48.5	19.4
16	Male	29	0.5	1.79	70.5	21.8
17	Male	20	18	1.90	81.6	25.2
Mean±SD		23.9±2.7	13.5±29.3	1.73±0.07	69.1±12.9	22.8±3.0

APPENDIX B: Determination of high knee loading movements of 42-form Tai Ji

Analysis of 42-form Tai Ji

In order to comprehensively understand the typical lower extremity movements of 42-form Tai Ji, we analyzed every single form of 42-form Tai Ji. According to previous Tai Ji lower extremity movement classification (28), we broke up the 42 forms into six fundamental movement categories: lunge, step, support, foot rotation, body weight shifting, and trunk rotation. For lunge and step, we also respectively classified lunge and step into four directional subcategories, forward, backward, sideway and diagonal. Depending on force distribution between two feet, we divided support into three subcategories as well, single leg support, double leg support, and pseudo support. Pseudo support means one-foot supports body weight with the other toe touching or heel touching the ground.

To facilitate the analysis of 42-form Tai Ji, we construct a table (Table 4). The six fundamental movements and their subcategories were assigned to the first row, while all the 42 forms Tai Ji movements were assigned to the first column. We watched each form movement video performed by Jiamin Gao, the national champion of Tai Ji in China. Then we checked the fundamental movement, which appeared during each 42-form movement. The analysis of the entire 42-form Tai Ji movements can be found in Appendix A.

Determination of high knee loading movements

After additional analyses of each movement from the 42-form Tai Ji, we further consolidated the movements into five most common lower extremity movements: forward lunge, lateral lunge, pseudo-step, horse stance, and single-leg support (Table 5). Depending on movement complexity and different levels of knee loading, we created three sub-categories, light loading, moderate loading and

high loading to the knee. We ignored some uncommon movements such as seated step, trunk rotation 360° and knee friendly movements such as open and close hands.

For the forward lunge category, if a form consists of a single forward lunge, such as left single whip, it was assigned to the light loading sub-category (Table 2). If a form consists of shifting body weight backward and forward based on a forward lunge, such as left grasp sparrow's tail, it was assigned to the moderate loading sub-category. If the form consists of multiple lunges starting from a forward lunge, shifting body weight backward, turning foot on heel with a trunk rotation 90 degree, and then with the trailing leg lunging forward again, it was assigned to the high loading sub-category.

The forms in the sideway lunge category were separated into moderate knee loading and high knee loading sub-categories depending on the height of their pose. Normally, the low pose lateral lunge was called push down. We assigned the pseudo-step which contains both toe touching and heel touching forms, to the moderate knee loading sub-category. Horse stance was assigned to the moderate knee loading sub-category, while the single leg support containing both lift and kick was assigned to high knee loading sub-category.

Finally we placed all of the movements with multiple lunges, pushdown and single leg support in the high knee loading subcategory. In the moderate loading sub-category, we also wanted to investigate the pseudo-step.

In order to more precisely and reasonably identify knee unfriendly movements that are commonly involved in 42-form Tai Ji. We distributed Knee Unfriendly Movement Selection Survey (Appendix C) via mail or email to Tai Ji experts. They were asked to fill out the survey based on our pre-selection. Two sections were included in the survey, demographic and attitudes sections. In the demographic

section we asked about the subject's practice and experience of Tai Ji. In the second section we asked the expert's opinion on pre-selected knee unfriendly movements in 42-form Tai Ji. The survey had English and Chinese versions as experts from US and China were sought.

Table 4. 42-form Tai Ji classification by movement patterns.

[Title]	Lunge			Step				Support				Foot Rotation		Shift BW		Trunk Rotation			
	1	2	3	1	2	3	4	single	Double	Pseudo		Heel	Forefoot	ML	AP	45˚	90˚	180˚	360˚
										toe	heel								
1. Commencing					√				√										
2. Right Grasp Sparrow's Tail $	√				√					√		√	√		√	√	√		
3. Left single whip $		√			√											√			
4. Lift hands						√					√	√		√	√	√	√		
5. White crane spreads its wings							√			√		√			√	√	√		
6. Brush knee and step forward	√											√			√	√			
7. Dodge body and throw fist	√											√			√	√			
8. Deflect and Shove			√									√		√	√	√			
9. Advance, parry and punch	√				√							√			√	√			
10. Apparent close up				√											√				
11. Open and close hands									√			√	√						
13. Fist under elbow				√		√					√	√		√	√	√			
14. Turn body and push palm				√			√			√		√					√	√	
15. Jade girl working with shuttles on both sides			√	√	√				√	√		√			√	√	√		
16. Heel kick on both sides	√	√						√				√			√	√			
17. Hind hands and strike fist		√							√*			√		√					
18 Paring the wild horse's mane on both sides	√				√				√			√		√	√		v		
19. Wave hands like clouds					√									√		√			
20. Beat tiger on single leg							√	√				√							
21. Right toes kick$								√											
22. Striking the opponent's ears with both fists	√																		
24. Turn body and slap foot					√#			√					√						√
25. Advance and punch down	√																√		
26. Flying obliquely		√*										√					√		

	Lunge			Step				Support				Foot Turning		Shift BW		Trunk Turning			
	1	2	3	1	2	3	4	Single	Double	Pseudo		Heel	Forefoot	ML	AP	45˚	90˚	180˚	360˚
										toe	heel								
27. Single whip and push down		√*												√			√		
28. Golden rooster stands on one leg								√				√							
29. Step back and pierce palm	√						√						√						
30. Press palm in empty stance										√*		√			√			√	
31. Stand on one leg and raise palm								√											
32. Lean and horse stance						√			√*			√		√					
33. Turn body and deflect					√		√					√	√	√			√		
34. Cross legged sitting and lock strike				√#*								√		√		√			
35. Pierce palm and push down	√	√*					√			√		√							
36. Step forward with seven stars	√			√						√		√		√			√		
37. Back step and straddle the tiger					√		√	√				√							
38. Turn body and lotus kick								√		√		√				√		√	
39. Bend bow to shoot tiger			√													√			
41. Cross hands	√				√							√			√		√		
42. Closing form					√				√										

1. Moving diagonal;
2. Moving backward;

Pseudo support: One foot supports with another toe touch or heel touch

$ Containing similar left and right movement patterns. No. 12, No. 23, No. 40 movements were omitted.

*low pose;

crossed legs;

Table 5. 42-form Tai Ji classification by knee loading

	Light Knee Loading	Moderate Knee Loading	High Knee Loading
Forward Lunge	3 left single whip 7 dodge body and throw fist 22 striking the opponent's ear with both fists 25 advance and punch down 29 step back and pierce palm 39 bend bow to shoot tiger	2 right grasp sparrow's tail 15 jade girl working with shuttles on both sides 40 left grasp sparrow's tail	6 brush knee and step forward 8 deflect and shove 9 advance, parry and punch 18 Paring the wild horse's mane on both sides
Pseudo-Step		4 lift hands 5 white crane spreads its wings 13 fist under elbow 30 press palm in empty stance 36 step forward with seven stars	
Sideway Lunge		12 right single whip 26 flying obliquely 33 turn body and deflect	27 single whip and push down 35 pierce palm and push down
Horse Stance		17 hind hands and strike fist 32 lean and horse stance	
Single Leg Support			16 heel kick on both sides 20 beat tiger on single leg 21 right toes kick 23 left toes kick 24 turn body and slap foot 28 golden rooster stands on one leg 31 stand on one leg and raise palm 37 back step and straddle the tiger 38 turn body and lotus kick

APPENDIX C: Knee Unfriendly Movement Selection Survey

42-Form Tai Ji Knee Unfriendly Movement Selection Survey

You are invited to participate in this survey of Knee Unfriendly Movements Selection in Tai Ji. The objective of this study is to select knee unfriendly movements that are commonly involved in 42-form Tai Ji. We are going to ask your opinion on our pre-selected movements. The results of this study will be used to further biomechanics study.

Your participation in this study will require completion of the attached survey. This should take approximately 15 minutes of your time. Your participation will be anonymous. And this survey does not involve any risk to you. We will be happy to answer any questions you have about this study. If you have further questions about this project, you may contact me, Chen Wen (cwen@utk.edu) or my advisor, Dr. Songning Zhang (szhang@utk.edu). By completing this survey, you will give your informed consent to participate in this study. Please complete the attached survey. Thank you.

Demographic Questions

Age: ___________________ Gender: Male / Female

1. Please circle the forms/styles of Tai Ji you can perform fluently. Please indicate how many years of experience you have practiced each form/style you selected.

Tai Ji Styles	Years of Experience
24-Forms	
42-Forms	
Sun Style	
Chen Style	
Yang Style	
Wu Style	
William Chang's Customized Style	

2. How many years of experience you have in teaching Tai Ji?

____

3. **Attitude Questions**

We are going to ask your opinion on our pre-selected Tai Ji movements. Please focus on lower extremities movements.

1. Multiple Lunges (example: brush knee and step forward)
Lunge forward, foot rotation on heel, trunk rotation 90 degree, then another leg lunge forward.

To what extent do you agree or disagree with the following statement (Check one)

	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
1. This movement is commonly involved in Tai Ji.					
2. It causes high loading to knee.					
3. People who suffering knee pain should avoid repetitive practice of this movement.					

Please leave some comments if you choose “strongly disagree” or “disagree”.

____

____

2. Push Down (example: single whip and push down)
Low pose sideway lunge.

To what extent do you agree or disagree with the following statement

	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
1. This movement is commonly involved in Tai Ji.					
2. It causes high loading to knee.					
3. People who suffering knee pain should avoid repetitive practice of this movement.					

Please leave some comments if you choose “strongly disagree” or “disagree”.

____

____

____

____

3. Horse Stance (example: hind hands and strike fist)
Horse stance and shift body medial lateral

To what extent do you agree or disagree with the following statement

	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
1. This movement is commonly involved in Tai Ji.					
2. It causes high loading to knee.					
3. People who suffering knee pain should avoid repetitive practice of this movement.					

Please leave some comments if you choose “strongly disagree” or “disagree”.

____

____

4. Kick (example: right toes kick)
Single leg support, then kick with toes forward.

To what extent do you agree or disagree with the following statement

	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
1. This movement is commonly involved in Tai Ji.					
2. It causes high loading to knee.					
3. People who suffering knee pain should avoid repetitive practice of this movement.					

Please leave some comments if you choose “strongly disagree” or “disagree”.

____

____

5. Are there any other movements you think are knee unfriendly and commonly involved in the 42-form Tai Ji?

____

____

6. Do you have any additional information that you think should be shared?

____

____

APPENDIX D: INFORMED CONSENT FORM

Investigator: Chen Wen and Songning Zhang (Faculty Advisor), Ph.D.
Address: Biomechanics/Sports Medicine Lab
The University of Tennessee Knoxville
1914 Andy Holt Avenue
Knoxville, TN 37996
Phone: 865-974-8768

INTRODUCTION
You are invited to participate in a research study entitled, "Knee Biomechanical Characteristics of Knee Unfriendly Movements in 42- form Tai Ji". The purpose of this research study is to identify movements that may be harmful to knee (knee unfriendly movements). The results of the study could help in movement selections and design of Tai Ji exercise routines for patients with knee pathological conditions, e.g., knee osteoarthritis (OA). This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand. Before agreeing to be in this study, it is important that you read and understand the following explanation of the procedures, risks, and benefits.

Testing Protocol and Duration
Before the testing session, if you do not have any Tai Ji experience, you will be offered a short training course to be taught by a Tai Ji master in which you will learn the selected Tai Ji movements and practiced those movements for a minimum of two weeks.

You will be asked to participate in one testing session which will last approximately 1.5-2 hours. At the beginning of the session, you will be asked to sign the informed consent form and to fill out a survey about your demographic information including Tai Ji experience and injury history and a PAR-Q form. You will then complete a self-directed warm up for 10 minutes, including 5 minutes of stretching of major lower extremity muscles and 5 minutes of practicing the selected Tai Ji movements before data collections. You should have prior knowledge of four selected Tai Ji movement, lunge, push down, kick and pseudo step. Reflective markers will be applied to your trunk and lower body. The markers will not interfere with your movements. You will be asked to perform five level walking trials. Then you will also be asked to perform five trials in each of eight Tai Ji movement conditions: lunge, push down and kick with each performed at a high pose and a low pose and two different pseudo steps, one with toe touch on the ground and another with heel touch on the ground. You will be given as much rest as needed between trials.

Potential RISKS
Risks for participating in the study are minimal. You will be asked to complete the warm up before data collections which will minimize potential risk of muscle strains. The selected Tai Ji movements are commonly used in popular Tai Ji routines and you should have already known how to perform these movements. In addition, the selected movements emphasize slow and fluid motion which should not post any high risk for injury. Consideration has been taken in Tai Ji movement selection to ensure that the movements are safe for participants. In general, Tai Ji exercise is slow, low impact, and easy to maintain balance.

All biomechanics tests and the handling of all equipment will be performed by qualified research personnel in the Biomechanics/Sports Medicine Laboratory. Complete instrumentation, measuring, and testing protocol will be disclosed to the subjects prior to their testing. If any injury should occur during the course of testing, standard first aid procedures

will be administered if needed. At least one researcher with a basic knowledge of first aid procedures will be present.

In the unlikely event a physical injury is suffered as a result of participation in this study (during the warm up and testing session), the University of Tennessee does not "automatically" reimburse subjects for medical claims or other compensation. If physical injury is suffered in the course of research, please contact Chen Wen (974-8768) or Dr. Songning Zhang (974-4716).

BENEFITS
You will learn basic Tai Ji movements that can improve their physical fitness. Results from the proposed study will identify movements that may be harmful to knee (knee unfriendly movements) could help in movement selections and design of Tai Ji exercise routines for knee OA patients.

CONFIDENTIALITY
Only the principal investigator, faculty advisor, qualified Biomechanics/Sports Medicine Laboratory personnel, will have access to the respective subject information and data. Data will be stored on hard drives of password protected computers in the Biomechanics/Sports Medicine Lab and will be backed up onto DVDs and/or portable hard drives, and erased from the hard drives after the completion of the study. All subject data will be coded numerically and referred to only by the code and not by subject name.

The results will be disseminated in the form of presentations, and/or publications. Subject information sheets, informed consent, and backup data DVDs and/or portable hard drives will be stored in a locked file cabinet in Rm 340, HPER building. The information sheets including the consent forms and other forms containing subject's identity information will be destroyed three years after the completion of the study. If subject decide to withdraw from the study, their information sheet, consent form and data with the identity will be destroyed. The cameras used in the study do not capture images of the subjects.

CONTACT INFORMATION
If you have questions at any time about the study or the procedures, you may contact the researcher, Chen Wen, at Biomechanics/Sports Medicine Lab, and 865-274-8768. If you have questions about your rights as a participant, contact the Office of Research Compliance Officer at (865) 974-3466.

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at anytime without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study
before data collection is completed your data will be returned to you or destroyed.

CONSENT
I have read the above information. I have received a copy of this form. I agree to participate in this study.

Participant's name __________Participant's signature ______________Date _________

Investigator's signature ________________________Date _________ Subject # ____

APPENDIX E: FLYER

UT RESEARCHERS ARE LOOKING FOR PARTICIPANTS TO STUDY Tai Ji!

A team of researchers from the Department of Kinesiology, Recreation and Sport Studies at UT are conducting research to study biomechanical characteristics of Knee Joint of Knee Unfriendly Movements in 42- form Tai Ji. Test participants will have chance to learn basic Tai Ji movements. Test and Control participants will be asked to attend one 1.5 – 2 hour testing sessions at the UT biomechanics laboratory.

You may be able to participate if

- You are between the ages of 18 and 30
- You have not major lower extremity and low back injuries
- You are interested in Tai Ji

If you'd like to participate, or would like more information, call **Chen Wen** at the UT Biomechanics/Sports Medicine Lab.

- **Office: (865) 974-8768**
- **E-mail: cwen@utk.edu**

Contact: Chen Wen
P: 865-235-3028
E: cwen@utk.edu

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APPENDIX F: PHYSICAL ACTIVITY READINESS QUESTIONAIRE (PAR-Q)

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ________________________________

SIGNATURE ________________________________ DATE ________________

SIGNATURE OF PARENT ________________________ WITNESS ________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

Supported by: Health Canada Santé Canada

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APPENDIX G INDIVIDUAL RESULTS FOR SELECTED VARIABLES

Table 6. Peak vertical GRF (BW)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	1.030±0.011	1.037±0.007	1.018±0.003	1.027±0.006	1.015±0.009	1.035±0.007	1.040±0.009	1.012±0.014
2	1.038±0.009	1.080±0.022	1.042±0.011	1.055±0.012	1.054±0.013	1.044±0.006	1.058±0.017	1.026±0.014
3	1.031±0.018	1.008±0.018	1.036±0.019	1.034±0.019	1.034±0.013	1.042±0.009	1.030±0.019	1.001±0.014
4	1.014±0.026	1.022±0.043	0.971±0.021	0.932±0.040	1.069±0.031	1.126±0.018	1.036±0.025	1.023±0.011
5	1.068±0.007	1.109±0.016	1.067±0.006	1.132±0.014	1.148±0.058	1.112±0.021	1.084±0.006	1.071±0.011
6	1.034±0.013	1.028±0.024	1.016±0.007	0.986±0.013	1.076±0.049	1.098±0.020	1.032±0.010	1.053±0.011
7	1.036±0.010	1.093±0.064	1.040±0.014	1.085±0.039	1.089±0.032	1.094±0.012	1.059±0.017	1.052±0.006
8	1.310±0.019	1.361±0.014	1.338±0.007	1.346±0.005	1.333±0.007	1.342±0.012	1.330±0.029	1.334±0.020
9	1.076±0.011	1.095±0.021	1.066±0.027	1.057±0.016	1.076±0.005	1.078±0.011	1.083±0.016	1.035±0.015
10	1.015±0.018	1.071±0.028	1.019±0.001	1.032±0.017	1.034±0.010	1.062±0.023	1.067±0.011	1.014±0.030
11	1.077±0.007	1.088±0.030	1.055±0.005	1.137±0.031	1.059±0.007	1.064±0.010	1.048±0.009	1.025±0.030
12	1.030±0.020	1.039±0.042	1.017±0.010	1.023±0.010	1.014±0.009	1.040±0.036	1.024±0.014	0.985±0.005
13	1.017±0.012	1.043±0.026	1.036±0.005	1.044±0.008	1.025±0.007	1.040±0.017	1.039±0.006	1.023±0.022
14	1.052±0.005	1.169±0.122	1.044±0.023	1.055±0.017	1.068±0.023	1.081±0.030	1.019±0.011	1.040±0.012
15	1.006±0.030	0.996±0.026	1.044±0.027	1.077±0.009	1.051±0.013	1.147±0.021	1.016±0.023	1.066±0.010
16	1.049±0.017	1.140±0.027	1.024±0.002	1.050±0.018	1.066±0.016	1.109±0.035	1.021±0.025	1.061±0.005
17	1.093±0.004	1.086±0.002	1.016±0.026	1.089±0.026	1.070±0.008	1.075±0.031	1.078±0.015	1.068±0.005
Mean±SD	1.057±0.069	1.086±0.085	1.050±0.078	1.068±0.087	1.075±0.073	1.093±0.072	1.063±0.072	1.062±0.077

Table 7. Peak knee flexion angle (degree)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	-39.981±1.353	-84.105±1.846	-40.227±5.152	-87.552±5.926	-47.248±3.919	-53.217±0.758	-66.552±4.810	-60.825±2.573
2	-33.325±2.246	-77.528±1.713	-35.088±3.150	-81.502±0.553	-13.971±8.440	-25.417±1.978	-52.724±1.131	-49.727±2.029
3	-44.967±5.510	-91.793±7.648	-49.073±2.589	-94.525±3.700	-15.165±1.336	-29.184±0.405	-47.999±2.643	-50.462±1.162
4	-33.142±0.647	-79.026±5.580	-32.337±3.292	-78.529±3.140	-15.252±4.194	-34.528±3.507	-52.435±4.957	-39.401±0.792
5	-31.699±0.631	-70.193±2.561	-28.199±3.702	-76.767±5.238	-43.970±6.483	-52.533±6.965	-73.774±6.050	-38.759±3.870
6	-44.899±2.409	-77.991±1.636	-40.621±4.236	-81.557±3.392	-15.957±0.571	-36.936±0.798	-48.162±1.181	-47.733±2.660
7	-28.991±2.688	-78.889±2.692	-32.092±1.465	-75.531±1.409	-12.261±0.098	-19.604±4.414	-55.325±1.678	-42.668±2.358
8	-41.509±5.940	-87.252±4.107	-37.290±5.629	-88.097±2.186	-29.194±4.135	-55.058±2.942	-36.359±2.363	-49.102±2.270
9	-33.723±3.892	-88.089±0.202	-42.759±1.375	-90.055±3.345	-32.027±1.812	-39.723±6.448	-65.677±7.575	-55.640±1.300
10	-35.054±1.067	-79.677±5.745	-35.838±0.502	-78.538±3.086	-23.837±2.878	-42.172±2.047	-56.284±5.046	-53.303±0.653
11	-49.322±3.174	-91.612±3.634	-38.771±0.381	-93.417±1.425	-21.927±1.098	-40.340±1.741	-47.961±1.528	-56.836±0.529
12	-42.726±4.164	-94.300±3.910	-50.293±0.961	-94.758±4.139	-26.788±1.696	-34.165±0.300	-67.995±3.374	-50.074±0.832
13	-22.732±4.293	-67.593±2.810	-25.527±2.439	-73.385±1.165	-5.942±2.580	-24.371±2.684	-46.953±2.399	-53.463±2.203
14	-52.186±3.536	-97.847±2.250	-47.288±4.353	-100.87±3.581	-36.966±2.205	-44.267±1.362	-77.605±3.046	-66.108±3.524
15	-36.748±1.072	-73.698±3.098	-41.408±4.968	-88.452±3.325	-3.463±0.399	-13.838±0.679	-60.287±3.633	-44.721±2.184
16	-42.456±8.413	-84.997±1.512	-41.349±0.848	-90.382±1.776	-24.578±2.597	-43.254±1.618	-61.967±1.982	-51.051±2.152
17	-40.234±5.372	-86.322±2.887	-37.250±4.788	-83.684±3.719	-39.837±5.621	-34.744±3.176	-56.596±2.334	-51.748±1.052
Mean±SD	-38.453±7.556	-82.995±8.465	-38.554±6.826	-85.741±7.841	-23.822±12.912	-36.746±11.520	-57.333±10.716	-50.684±7.075

Table 8. Peak knee flexion ROM (degree)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	-37.314±3.868	-83.393±5.566	-10.018±5.383	-39.308±3.744	-16.234±7.082	-17.869±4.791	-34.597±4.265	-53.094±2.386
2	-22.116±3.153	-66.643±7.012	-22.597±4.168	-66.851±4.947	-9.812±8.371	-20.783±0.901	-49.522±1.757	-48.748±2.085
3	-41.492±5.644	-86.116±8.677	-32.583±2.099	-76.919±4.843	-1.683±1.971	-14.953±1.563	-33.797±4.886	-47.936±1.199
4	-26.788±9.506	-72.477±3.179	-29.035±3.490	-62.004±11.607	-10.266±5.636	-21.894±7.079	-38.860±11.230	-41.799±3.259
5	-28.599±3.739	-64.755±5.897	-11.515±3.028	-58.956±13.814	-19.310±6.286	-10.922±13.390	-35.890±12.251	-45.555±5.164
6	-33.803±1.365	-69.258±1.842	-25.380±3.718	-66.269±3.158	-5.648±0.796	-18.956±3.515	-31.238±1.851	-46.060±2.369
7	-24.065±5.145	-67.135±3.738	-29.823±2.566	-60.636±10.213	-8.685±7.320	-13.039±7.105	-58.119±1.787	-37.101±2.445
8	-34.019±5.696	-78.448±3.445	-25.835±4.270	-72.673±2.729	-17.751±1.446	-47.057±2.914	-31.336±2.773	-47.837±2.503
9	-31.966±5.796	-78.324±4.577	-26.560±9.391	-85.752±5.777	-6.656±1.013	-27.267±16.033	-61.709±9.569	-56.371±2.129
10	-28.705±5.758	-69.705±6.414	-33.730±2.683	-72.908±12.486	-17.216±11.219	-41.675±4.357	-57.483±5.566	-49.153±1.309
11	-38.328±2.993	-78.115±2.837	-7.844±3.752	-65.554±4.388	-5.979±1.790	-13.400±3.279	-15.816±6.467	-50.112±1.234
12	-24.638±3.186	-75.521±2.113	-33.656±1.272	-78.906±3.849	-8.458±1.516	-14.488±3.388	-49.631±3.294	-38.500±1.917
13	-26.576±2.474	-72.838±3.157	-26.268±1.194	-75.080±2.664	-10.614±1.966	-31.212±2.304	-52.215±1.246	-65.180±0.475
14	-26.291±8.421	-67.027±1.316	-14.992±8.635	-68.064±4.216	-13.061±5.007	-21.828±9.082	-60.783±4.096	-47.082±2.952
15	-20.209±2.683	-47.591±0.936	-30.858±5.764	-82.623±3.226	-2.137±0.492	-12.739±2.558	-56.317±4.871	-40.300±3.129
16	-30.046±2.340	-69.962±1.671	-34.462±1.818	-82.929±3.816	-16.244±3.304	-29.565±6.501	-52.876±4.072	-48.530±2.372
17	-27.316±5.409	-71.836±3.011	-17.436±3.494	-53.951±14.155	-24.439±16.296	-22.440±9.186	-45.221±4.837	-49.647±2.774
Mean±SD	-29.545±5.887	-71.714±8.669	-24.270±8.774	-68.787±11.829	-11.123±6.334	-22.649±9.947	-45.024±13.044	-47.824±6.696

Table 9. Peak knee adduction ROM (degree)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	13.205±0.910	32.506±0.021	6.390±2.023	11.957±3.282	8.624±2.265	14.484±1.177	21.992±1.046	1.105±0.561
2	16.811±3.141	39.718±1.020	6.267±1.694	6.452±1.016	2.445±0.972	3.068±0.562	19.772±0.766	1.325±1.929
3	11.992±3.199	32.595±2.607	8.569±2.358	14.540±2.119	0.421±0.356	0.537±0.529	11.955±1.568	0.845±0.051
4	13.824±2.418	23.328±3.286	5.509±0.165	12.434±2.367	0.583±0.784	0.866±0.069	12.417±1.644	2.977±0.342
5	4.935±1.372	16.504±2.046	4.771±0.809	9.845±3.665	4.668±2.284	4.891±3.549	22.683±0.472	0.039±0.044
6	15.515±1.321	22.661±0.861	6.088±4.217	2.847±4.494	1.654±1.891	2.108±1.219	13.103±4.855	3.252±1.235
7	13.216±1.790	28.857±1.603	11.147±1.141	16.811±5.398	2.711±0.614	2.268±0.970	15.477±2.776	1.646±0.143
8	11.353±0.884	18.911±0.320	5.904±1.059	8.914±0.963	3.885±1.186	7.492±0.551	10.506±2.302	2.407±1.275
9	13.595±4.860	34.807±3.271	9.764±2.016	9.162±2.204	0.936±0.605	0.205±1.364	18.743±1.617	2.735±0.310
10	12.061±0.643	24.233±0.869	9.882±3.391	16.148±6.252	2.285±2.738	2.616±1.589	21.720±2.048	0.914±0.532
11	13.238±2.768	19.234±2.435	4.741±0.372	11.280±1.416	3.987±0.193	2.025±0.166	9.713±1.618	4.088±0.020
12	12.110±1.879	27.218±1.519	13.279±2.746	15.647±4.425	0.627±0.717	0.736±0.645	17.660±1.992	0.811±0.470
13	17.585±2.666	31.551±5.060	8.193±1.136	18.226±0.701	3.287±1.282	2.826±0.881	13.098±1.439	4.722±1.143
14	13.709±4.831	27.230±0.356	8.367±2.591	4.938±2.906	3.665±1.788	2.562±3.098	18.728±2.535	0.219±0.192
15	12.753±0.455	23.316±1.393	4.536±1.395	5.009±2.414	1.024±0.405	1.972±0.105	22.893±5.651	0.459±0.078
16	7.534±1.384	13.447±1.949	2.110±0.640	1.255±0.887	0.838±1.280	1.157±0.258	12.299±0.327	0.104±0.091
17	20.781±2.619	26.946±2.273	4.498±1.541	14.469±1.678	4.115±4.453	3.237±2.813	17.405±1.668	2.880±1.027
Mean±SD	13.189±3.570	26.063±6.922	7.060±2.848	10.584±5.139	2.692±2.092	3.120±3.411	16.480±4.476	1.796±1.444

Table 10. Peak knee external rotation ROM (degree).

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	-14.664±1.809	-19.066±2.219	-15.923±2.450	-4.397±0.487	-11.466±2.977	-16.348±1.896	-18.177±0.751	-
2	-20.229±1.082	-22.364±2.226	-15.856±3.315	-18.428±1.733	-3.989±1.092	-5.559±1.556	-20.251±2.190	-
3	-8.611±4.833	-9.758±1.041	-12.190±4.882	-4.599±0.866	-0.485±1.057	-0.200±1.077	-0.592±2.802	-
4	-6.168±2.104	-11.757±1.229	-26.305±3.124	-29.275±3.579	-2.266±1.195	-2.013±0.567	-17.663±8.111	-
5	-17.812±3.140	-23.892±3.398	-20.450±3.524	-25.438±0.622	-7.918±3.105	-5.171±4.562	-19.174±4.429	-
6	-14.003±1.558	-11.726±2.970	-30.560±2.972	-21.676±2.021	-4.706±3.985	-1.694±2.055	-23.186±6.748	-
7	-19.541±2.050	-17.074±2.335	-21.407±3.438	-9.781±10.066	-5.943±5.180	-5.762±0.949	-6.688±5.663	-
8	-2.730±0.988	-6.865±6.870	-21.369±3.278	-1.421±4.548	-4.488±1.422	-0.416±0.721	-7.350±1.332	-
9	-12.730±4.846	-22.934±2.323	-18.652±3.127	-2.850±0.561	-1.618±0.552	-0.287±0.497	-9.338±4.536	-
10	-11.958±4.601	-17.348±4.122	-36.460±2.247	-34.858±3.559	-4.686±4.271	-13.766±2.800	-21.703±1.265	-
11	-16.228±2.612	-19.644±3.460	-18.644±2.253	-10.514±4.111	-3.229±0.335	-1.426±0.972	-10.976±1.862	-
12	-11.286±2.036	-14.313±1.194	-17.563±1.168	-14.447±1.634	-0.685±0.604	-0.978±0.190	-5.117±0.666	-
13	-16.316±1.827	-20.499±3.219	-26.530±2.577	-16.001±2.504	-3.188±1.167	-2.236±0.323	-22.539±3.917	-
14	-16.023±5.863	-26.651±4.158	-15.624±2.434	-12.363±0.866	-1.477±2.412	-3.411±2.417	-15.629±0.430	-
15	-5.628±1.973	-12.257±6.322	-16.781±3.635	-9.086±1.023	-7.030±0.887	-0.715±0.293	-11.702±2.549	-
16	-8.224±1.469	-11.443±1.793	-7.569±2.445	-3.601±3.778	-0.427±0.409	-0.120±0.013	-11.750±0.977	-
17	-15.547±5.065	-3.955±4.573	-12.256±3.461	-16.327±2.352	-0.632±0.604	-0.898±0.118	2.504±3.567	-
Mean±SD	-12.806±5.068	-15.973±6.381	-19.655±7.138	-13.827±9.730	-3.778±3.043	-3.581±4.728	-12.902±7.768	-

Table 11. Peak knee peak extensor moment (Nm/kg)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	0.957±0.089	1.193±0.129	1.142±0.146	2.004±0.130	1.191±0.093	1.347±0.051	1.630±0.180	0.833±0.037
2	0.799±0.093	1.618±0.021	0.808±0.076	1.825±0.055	0.188±0.059	0.502±0.027	1.308±0.031	0.406±0.072
3	1.123±0.098	1.889±0.059	1.222±0.119	1.803±0.028	0.255±0.014	0.719±0.078	1.262±0.088	0.236±0.053
4	0.894±0.140	1.308±0.120	0.764±0.169	1.482±0.182	0.191±0.259	1.156±0.139	1.368±0.090	0.375±0.074
5	0.950±0.127	1.915±0.069	0.776±0.173	1.838±0.031	1.162±0.241	1.502±0.071	1.756±0.046	0.261±0.017
6	1.060±0.073	1.377±0.100	0.763±0.227	1.389±0.115	0.023±0.120	0.643±0.099	1.219±0.078	0.217±0.071
7	1.115±0.028	2.236±0.124	1.115±0.107	2.290±0.100	0.344±0.101	0.524±0.132	1.692±0.183	0.503±0.043
8	1.436±0.364	2.557±0.205	1.733±0.238	3.406±0.104	1.118±0.155	2.153±0.139	1.645±0.211	0.300±0.011
9	1.189±0.120	1.852±0.166	1.121±0.128	2.321±0.114	0.951±0.034	1.088±0.199	1.842±0.117	0.374±0.027
10	0.842±0.181	1.929±0.117	0.743±0.071	1.580±0.173	0.440±0.043	1.073±0.127	1.458±0.157	0.669±0.005
11	1.203±0.008	1.768±0.086	1.117±0.019	2.525±0.109	0.424±0.039	1.030±0.053	0.953±0.086	0.282±0.017
12	1.174±0.010	1.838±0.083	1.299±0.069	2.049±0.060	0.359±0.067	0.639±0.024	1.610±0.058	0.321±0.057
13	0.705±0.153	1.655±0.164	0.788±0.038	1.845±0.256	0.116±0.261	0.808±0.124	1.483±0.158	0.224±0.000
14	1.210±0.064	2.058±0.149	1.268±0.168	2.358±0.086	0.626±0.070	0.933±0.085	1.790±0.072	0.680±0.021
15	0.688±0.149	1.414±0.229	0.905±0.171	1.539±0.097	0.169±0.044	0.185±0.084	1.436±0.115	0.188±0.027
16	1.318±0.262	1.680±0.163	0.951±0.098	1.812±0.033	0.483±0.005	1.347±0.070	1.372±0.019	0.352±0.031
17	0.958±0.232	1.266±0.058	0.705±0.114	1.292±0.038	0.451±0.032	0.533±0.105	1.047±0.035	0.171±0.020
Mean±SD	1.037±0.212	1.738±0.362	1.013±0.276	1.962±0.514	0.477±0.410	0.952±0.471	1.463±0.256	0.376±0.190

Table 12. Peak knee abduction moment (Nm/kg)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	-0.627±0.053	-0.819±0.059	-0.448±0.006	-0.435±0.061	-0.571±0.016	-0.588±0.051	-0.694±0.010	-0.328±0.037
2	-0.441±0.022	-0.952±0.049	-0.350±0.030	-0.335±0.021	-0.376±0.029	-0.351±0.027	-0.691±0.055	-0.266±0.049
3	-0.493±0.062	-0.659±0.040	-0.442±0.014	-0.410±0.043	-0.356±0.027	-0.428±0.034	-0.591±0.053	-0.289±0.035
4	-0.512±0.114	-0.447±0.058	-0.432±0.013	-0.329±0.144	-0.435±0.058	-0.462±0.011	-0.457±0.068	-0.442±0.065
5	-0.315±0.040	-0.318±0.044	-0.276±0.037	-0.217±0.118	-0.149±0.040	-0.017±0.033	-0.295±0.090	-0.160±0.032
6	-0.513±0.111	-0.360±0.088	-0.359±0.091	-0.367±0.062	-0.377±0.058	-0.380±0.024	-0.479±0.076	-0.351±0.005
7	-0.707±0.031	-1.230±0.109	-0.683±0.185	-0.608±0.177	-0.585±0.003	-0.576±0.067	-0.697±0.103	-0.477±0.020
8	-0.563±0.040	-0.791±0.094	-0.528±0.046	-0.665±0.119	-0.674±0.041	-0.684±0.018	-1.045±0.047	-0.614±0.060
9	-0.661±0.040	-1.023±0.061	-0.674±0.152	-0.282±0.042	-0.324±0.056	-0.355±0.086	-0.639±0.059	-0.405±0.061
10	-0.453±0.073	-0.714±0.083	-0.302±0.093	-0.324±0.035	-0.384±0.057	-0.354±0.034	-0.628±0.060	-0.295±0.006
11	-0.658±0.092	-0.688±0.052	-0.322±0.065	-0.732±0.048	-0.510±0.014	-0.453±0.023	-0.556±0.027	-0.448±0.043
12	-0.494±0.027	-0.673±0.010	-0.306±0.031	-0.681±0.191	-0.405±0.032	-0.403±0.026	-0.637±0.026	-0.291±0.024
13	-0.473±0.041	-0.548±0.151	-0.648±0.140	-0.389±0.053	-0.572±0.017	-0.550±0.054	-0.709±0.046	-0.459±0.014
14	-0.671±0.055	-0.646±0.106	-0.282±0.019	-0.758±0.213	-0.485±0.039	-0.494±0.063	-0.623±0.039	-0.427±0.013
15	-0.446±0.098	-0.779±0.113	-0.290±0.056	-0.444±0.122	-0.322±0.025	-0.354±0.013	-0.588±0.169	-0.170±0.011
16	-0.532±0.048	-0.507±0.140	-0.550±0.027	-0.429±0.073	-0.370±0.025	-0.360±0.025	-0.465±0.062	-0.402±0.023
17	-0.571±0.060	-0.687±0.049	-0.433±0.096	-0.420±0.033	-0.509±0.025	-0.505±0.040	-0.634±0.049	-0.371±0.039
Mean±SD	-0.537±0.103	-0.697±0.233	-0.431±0.141	-0.460±0.165	-0.436±0.127	-0.430±0.146	-0.613±0.156	-0.364±0.115

Table 13. Peak knee internal rotation moment (Nm/kg)

Subject	Lunge		Pushdown		Kick		Pseudo-step	Walking
	high	low	high	low	high	low		
1	0.244±0.034	0.564±0.022	0.254±0.040	0.452±0.005	0.287±0.002	0.356±0.002	0.497±0.044	0.142±0.009
2	0.124±0.027	0.325±0.030	0.140±0.017	0.284±0.004	0.042±0.010	0.072±0.019	0.284±0.008	0.114±0.002
3	0.236±0.051	0.354±0.047	0.158±0.017	0.266±0.025	0.084±0.009	0.108±0.004	0.305±0.033	0.058±0.019
4	0.179±0.029	0.276±0.078	0.101±0.026	0.153±0.033	0.060±0.001	0.207±0.056	0.390±0.042	0.036±0.024
5	0.229±0.010	0.494±0.042	0.190±0.024	0.461±0.044	0.314±0.046	0.307±0.031	0.588±0.063	0.119±0.012
6	0.379±0.030	0.558±0.028	0.205±0.110	0.200±0.040	0.023±0.011	0.147±0.024	0.316±0.045	0.110±0.013
7	0.219±0.010	0.517±0.114	0.219±0.021	0.454±0.081	0.069±0.018	0.106±0.036	0.403±0.022	0.120±0.004
8	0.273±0.103	0.618±0.038	0.289±0.066	0.499±0.021	0.270±0.037	0.413±0.038	0.424±0.065	0.133±0.024
9	0.182±0.037	0.465±0.036	0.210±0.042	0.215±0.030	0.198±0.019	0.184±0.029	0.366±0.015	0.046±0.034
10	0.213±0.060	0.488±0.008	0.173±0.030	0.351±0.055	0.106±0.025	0.153±0.044	0.450±0.038	0.238±0.010
11	0.338±0.037	0.631±0.047	0.278±0.016	0.738±0.050	0.116±0.012	0.217±0.021	0.262±0.015	0.106±0.014
12	0.300±0.048	0.659±0.077	0.333±0.007	0.486±0.057	0.116±0.016	0.128±0.041	0.528±0.062	0.134±0.023
13	0.207±0.029	0.552±0.108	0.208±0.012	0.422±0.046	0.024±0.048	0.214±0.029	0.397±0.047	0.037±0.012
14	0.372±0.028	0.730±0.179	0.254±0.016	0.307±0.044	0.224±0.027	0.270±0.008	0.377±0.038	0.235±0.013
15	0.201±0.067	0.534±0.021	0.197±0.061	0.216±0.074	0.030±0.009	0.018±0.006	0.397±0.073	0.058±0.028
16	0.282±0.043	0.715±0.113	0.124±0.043	0.226±0.069	0.075±0.010	0.169±0.008	0.394±0.017	0.093±0.010
17	0.267±0.048	0.431±0.034	0.154±0.008	0.317±0.030	0.128±0.010	0.135±0.017	0.389±0.029	0.093±0.015
Mean±SD	0.250±0.069	0.524±0.129	0.205±0.062	0.356±0.149	0.127±0.096	0.189±0.102	0.398±0.085	0.110±0.059

VITA

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