MOTION PATTERN OF THE HEALTHY YOGA PRACTITIONER – KINETICS AND KINEMATICS OF THE LOWER EXTREMITY DURING THREE YOGA POSTURES AND COMPARISON TO THREE ACTIVITIES OF DAILY LIVING

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Abstract

The purpose of this study was to establish a motion pattern by characterizing the kinetics and kinematics associated with the hip, knee and ankle joint of a group of healthy yoga teachers when performing three yoga postures and comparing them to three activities of daily living (ADL). A group of experienced female yoga practitioners (n = 13), with a minimum of 5 years teaching experience, between the ages of 20 to 45, performed the Lunge, Warrior II, and Triangle poses starting from Downward Dog. The kinetic and kinematic data of the yoga practitioners was collected when performing yoga postures. The step length, joint angles, range of motion (ROM), joint moments, and angular impulse in sagittal and frontal plane were studied for the hip, knee and ankle during performance. The data were averaged, descriptive statistics of the measures were obtained, and results for each posture as well as for the average yoga practice were presented in tables and figures with standard deviation. The percentages of change and effect sizes were calculated to compare yoga movements to ADL. The stride lengths were similar in the Lunge (1.98m), Warrior II (1.51m), and Triangle (1.43m). The motion patterns of the Lunge and the Warrior II poses follow similar joint angle and joint moment, and angular impulse patterns, whereas the Triangle pose creates distinctly different patterns in most joints and planes. In the Lunge and Warrior II poses, the knee joint reaches a maximal flexion angle of 73.76° and 67.69° respectively, 18% to 32% less than what is classically instructed in a yoga class. The knee reached 9.5° of extension while in Triangle pose. The hip contributed 50-70% of the angular impulse in the lower limb in all three yoga movements. When comparing to ADL, ROM was only greater in the hip in of sagittal plane motion and in the knee if frontal plane motion, and most of the joint moments of the lower extremity were notably smaller

in ADL for the minimal values and notably larger for the maximal values in yoga. In conclusion, this is first time to establish the kinematics and kinetics motion patterns of three yoga movement which become a basis for further studying yoga biomechanics and its application. Moreover the motion pattern data suggests that yoga experts do not yoga as practice the Lunge and Warrior poses as classically described in yoga book for the knee and Triangle pose may place the knee in a precarious alignment. Yoga has high demanding to hip strength and ROM, which may help to improve hip strength and subsequently benefit to dynamic stability in gait.

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This piece of work, however miniscule in the world academia, has been my most challenging project to date. It was conceived in order to prove to the academic world that my passion, yoga, is so much more than a sport. That yoga can be a therapy.

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1 Introduction

1.1 Background

Yoga is a physical and mental discipline that was developed in India over 2000 years ago and is gaining popularity in Western societies (Roland, Jakobi, & Jones, 2011). It is being practiced in health clubs, private studios and homes all over North America (Hagins, Moore, & Rundle, 2007). It is estimated that participation has tripled between 2006 and 2011 (Roland et al., 2011). In a recent survey, researchers found that 6.9% of Americans are practicing yoga, with an additional 18.3 million expressing an interest in trying it (Roland et al., 2011). Many participants practice yoga to treat neck and back pain (Williams et al., 2005) and improve overall mental and physical health (Hayes & Chase, 2010). Western doctors and therapists are recommending yoga to their patients as a medical therapy (Hayes & Chase, 2010). In the growing field of yoga therapy, professionals are seeking to establish yoga as an independently viable healing practice, as well as integrate it into the current Western medical model (Hayes & Chase, 2010). However, as with the evaluation of all therapies seeking legitimacy, evidence of yoga therapy's benefits must withstand the scrutiny of the scientific inquiry (Uhlig, 2012). In an article by Mueller (2002), the author cautions health authorities and potential yoga participants about the risks of selecting an inappropriate yoga style, studio and teacher for the specific needs of the individual. Further evaluation of the benefits of yoga will aid health care providers and fitness professionals in recommending the most beneficial yoga practice to their patients (Cowen & Adams, 2005; Hayes & Chase, 2010).

Research has been completed in various fields of yoga, but few studies focused on the biomechanics of yoga. There are few studies directly exploring the kinetics and kinematics of yoga movement, and as a result, the gaps in the scientific literature are great and there is a limited understanding of the health implications related to the proper and efficient biomechanics of yoga when compared to activities of daily living (ADL). In a critical review by Roland et al. (2011), the authors enumerate a number of concerns with studies emerging in the field of yoga. They recommend that studies include larger sample sizes, that researchers should utilize reliable assessment instruments and that they must specify inclusion and exclusion criteria. For example, in a pilot study conducted by Westwell, Bell, and Õunpuu (2006), the yogic movements of one male participant were analyzed. The results of the study could not be statistically significant, yet the researchers reported a number of clinical applications (i.e. comparing yoga to other exercises as well as using the motion pattern as a way to optimize yoga performance while reducing and treating injuries). Without an adequate sample size, such comparisons with various therapies and physical activities should not be used as the basis for universal applications. More participants were recruited to complete DiBenedetto et al. (2005) study where a total of 19 healthy older participants (aged 62-83 years) completed the 8-week yoga intervention program exploring the changes in gait. Based on pre and post-intervention measurements there was an increase in stride length and peak hip extension as well as a trend towards reduced average pelvic tilt based on yoga practice frequency. In this study however, no kinematic data was collected throughout the yoga movements, therefore it is unclear what mechanism led to these gait changes. Many cross-sectional studies are in agreement that the practice of yoga leads to improved mobility based on improved isokinetic and isometric muscle strength and joint flexibility (Tran, Holly, Lashbrook, & Amsterdam, 2001), increased range of motion (ROM) (M. S. Garfinkel, Schumacher Jr, Husain, Levy, & Reshetar, 1994; Haslock, Monro, Nagarathna, Nagendra, & Raghuram, 1994) reduced pain in those with osteoarthritis (OA) (M. S. Garfinkel et al., 1994; M. S. Garfinkel et al., 1998), improved balance and coordination in elderly patient with stroke (Bastille & Gill-Body, 2004). Data on the kinetics and kinematics common activities of daily living is available. Data of level walking, stair ascent and stair descent has been previously acquired in our lab (N. H. Law, 2013; Lee, 2011) (table 6). This information (table 10 and 20) is useful as it provides a clear reference point for the minimum standards necessary to complete the required activity. It is reported that gait is improved with the practice of yoga, further studies may help determine what other ADL can be improved with this practice. Yoga shows promise as a means of improving ADL capacity in older adults. If yoga is to fulfill this promise as an attractive and inexpensive way to improve the quality of life and maintain functional mobility, it is important to understand the movement pattern and caution any restrictions or modifications before prescribing it.

Though yoga is often viewed as a form of therapy and healing, it is important to highlight that the practice of yoga can also cause injury (Bianchi, Cavenago, & Marchese, 2004; Fishman, Saltonstall, & Genis, 2009; Patel & Parker, 2008). In a survey where 1336 Yoga teachers responded (Fishman et al., 2009), the structures believed to be most at risk were the cervical spine, the low back and the knees. It was believed by surveyed participants that yoga injuries most often occurred due to poor technique or position alignment, previous injuries, excess effort, and insufficient instructions from the yoga instructor. Studying yoga movement helps to shed light on potential mechanisms of injury by using the motion pattern as baseline values in future intervention research in order to suggest precautions.

1.2 Research Question and Purpose

The purpose of this study was firstly, to characterize three yoga postures using the kinetics and kinematics of the hip, knee and ankle joint for a group of healthy yoga teachers, and secondly, to compare these characteristics to those of ADL in level walking, ascending stair, and descending stair walking. This research primarily aims to answer the question; what are the quantitative descriptors of the properly executed yoga movement? The secondary research question is; what are the differences in the kinetics and kinematics between yoga movements and activities of daily living? Specifically to the data previously established for walking as well as ascending and descending stairs (N. H. Law, 2013; Lee, 2011). The answers to these questions fills some of the gaps in the scientific literature on yoga identified above by thoroughly analyzing the typical yoga movements, how they compare to typical daily movements and by determining if yoga can serve as way to improve capacities for ADL in a healthy population.

1.3 Variables

1.3.1 Movement of study

According to recent review, there are over 840 000 yoga postures (Raub, 2002) but Iyengar (Iyengar, 1982) describes only 57 basic postures in his text based on traditional Iyengar Yoga, of which thousands of variations can be derived. The Crescent lunge pose (*Alasana*), Warrior II pose (*Virbradasana II*) and Triangle pose (*Trikonasana*), were studied in order to characterize the motion pattern of these yoga movements. These three postures were chosen because they are commonly found in various styles of yoga practice and are described at length in Hatha yoga textbooks (Coulter, 2001; Iyengar, 1982; Kaminoff; M. Kirk & Boon, 2006). Many variations of these poses can be derived (Figure 1) from these fundamental standing yoga postures (Coulter, 2001; Kaminoff; M. Kirk & Boon, 2006) such as the Extended Side Angle which resembles a combination of Warrior II and Triangle pose or even the several different versions of the lunges, all of which resemble the Crescent lunge pose. These postures are largely related to most standing yoga and are also taught as introductory poses in many beginner Hatha yoga classes as an intermediary step to more advanced poses. As a way to standardize the study, as well as mimic a typical yoga practice, the researchers asked that participants begin in an initial posture, in Downward Dog (*Adhas Mukha Svanasana*), and move to the final poses of Crescent lunge, the Warrior II and the Triangle, always returning to the initial posture, Downward Dog, between trials and poses.

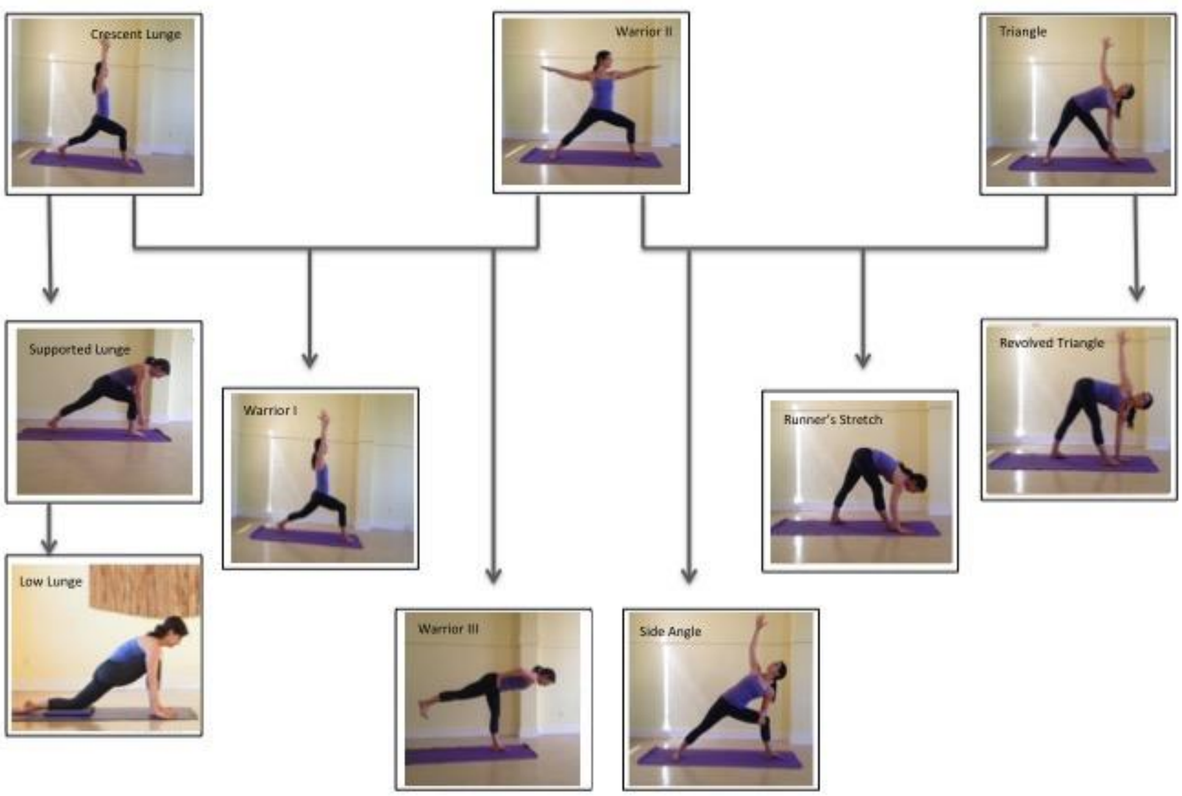

Figure 1 Flow chart representing the interconnectedness of fundamental and more advanced Yoga postures.

1.3.2 Variables Studies

This study focused on analyzing the following variables during yoga movements. The data obtained from yoga movements was compared to data previously acquired in our laboratory for level walking, stair ascent and stair descent (N. H. Law, 2013; Lee, 2011).

a) Spatial and Kinematic

Exploring the spatial parameters establishes a link between yoga movements and gait, and in doing so, lead to a greater understanding on how yoga may relate to the ADL functions stair and level walking. Studying the joint range of motion (ROM) allows for a greater understanding of the yoga practitioners' orientation in space and specifies the flexibility required to achieve the yoga movement.

Hence, the spatial and kinematic parameters studied are the step length and joint angles(°) of the hip, knee and ankle during yoga movements. Furthermore, the mean value of the maximum and minimum angles of each joint was used to calculate the ROM in the sagittal and frontal planes during the yoga movements.

b) Kinetic

The kinetic parameters that were included in this study served to describe the body responses when participant connect with the ground. Specifically, it described the amplitude of the force during the contact, the duration of this foot strike and the joint moments in the lower body. Quantifying the net joint moments served as a way to describe how this type of physical activity impacts the joints of the lower extremity, thereby gaining a greater understanding on how yoga movements can impact physical capacity for joints to bear loads.

Therefore, the kinetic parameters included the peak ground reaction force (GRF) represented as a percentage of the participant's body weight (%BW) at foot strike, the impulse (N•s) between the start of movement and the instance of the peak GRF, the peak joint moments of force (Nm/kg) and angular impulse (N•m•s) of the hip, knee and ankle of the entire yoga movements.

1.4 Hypothesis

The practice of yoga can be visually characterized by large slow movements where participants can be standing, seated, laying supine, or prone. Depending on the style of practice, the postures can be linked in continuous movements, while others are held for 30 seconds to several minutes. Yoga practitioners are often instructed to move softly, making soundless hand or foot contact with the ground. We expected the yoga motion pattern to express long step lengths and large peak joint angles, based on the findings of pilot yoga study (DiBenedetto et al., 2005). Furthermore, we also expected increased ROM when compared to walking and stair climbing (N. H. Law, 2013), as previous studies (Cowen & Adams, 2005; Schmid, Van Puymbroeck, & Koceja, 2010) have reported an increased flexibility following yoga interventions. We anticipated GRF to be significantly less than walking because of the slow and stable nature of movements in yoga, similar to those found in a Tai Chi study performed in our laboratory (N.Y. Law, 2011). Consequently, we expected to observe small impulse upon foot strike implying a reduced loading rate, making yoga safe alternative to high joint impact physical activities. Despite the lower GRF and impulse, previous research on yoga movements (Omkar, Mour, & Das, 2011; Westwell et al., 2006) lead us to hypothesize that the joint moments of force would be similar to those of ADL as stated by Lee (2011) and N. H. Law (2013). Measuring these kinetic and kinematic parameters and comparing them to those known for ADL allowed us to determine if yoga practice as an appropriate training method for physical fitness improvements towards functional mobility.

The hypotheses are as follows:

1) The ROM of the lower extremity joints during yoga movements will be greater when compared to the ROM during two activities of daily living: walking and stair climbing;
2) Peak joint moments during Yoga movement will be equal or greater when compared to those already known for those during walking and stair climbing.

1.5 Relevance of Study

Many studies have been conducted exploring the effects of stretching on various fitness outcomes, but few have explored the stretching specifically from yoga postures. In studies related to biomechanics of yoga, the following topics have been examined: joint moments (Omkar et al., 2011; Westwell et al., 2006), stride length (DiBenedetto et al., 2005), flexibility (Schmid et al., 2010; Williams et al., 2005), postural stability and balance (Schmid et al., 2010; Silver & Butcher Mokha, 2005), and intervention programs using yoga as therapy to treat pain (Tekur, Nagarathna, Chametcha, Hankey, & Nagendra, 2012; Williams et al., 2005) and more specifically back pain (Sherman et al., 2010; Tekur et al., 2012) as well as treating osteoarthritis (Uhlig, 2012).

To the author's knowledge, there are 6 studies directly exploring the kinetics and kinematics of yoga movement (Cowen & Adams, 2005; DiBenedetto et al., 2005; Omkar et al., 2011; Schmid et al., 2010; Tran et al., 2001; Westwell et al., 2006), and of these studies only 2 tested a relatively large amount of participants (n = 23 DiBenedetto et al.; n = 26

Cowen & Adams) . Therefore this study contributes to the scientific understanding of yoga movements, establishing a motion pattern that presently remains unknown and determine how yoga movements compare to walking and stair ascent and descent and provides an understanding of the relationship between yoga as an activity and locomotion.

Theoretical understanding begins with descriptive studies, they are the first step into a new topic (Winter, 2004). Specifically, researchers (Omkar et al., 2011; Westwell et al., 2006) highlight the importance of evaluating the joint moments generated during yoga, as it is a classical process, and the conventional method, in human movement analysis. Further variables such as the joint angles complement the motion pattern. Motion analysis is an important stage in biomechanical studies, as the detailed quantitative description of the motion pattern of the ideal movement allows for reference point in which to evaluate application, establish intervention programs, understand how to improve technical skills and keep abilities at the top level, and eventually comprehend how to prevent injuries (Hong & Bartlett, 2010). The motion pattern firstly serves as way to understand the training and therapeutic mechanism of yoga movement and in the future it will provide values to base comparisons to various ages and pathologies as well as to other forms of exercise. In this case, the study of the expert yoga practitioner establishes the properly executed movement pattern, the "gold standard", and compares the kinetic and kinematic characteristics to those of two basic ADL.

In a critical review, Roland et al. (2011) suggested that studies should be standardized within and across the various yoga disciplines namely by exclusively studying one style of yoga and by clearly defining the yoga program, with images or detailed description, taught during interventions. Unfortunately, narrowing our sample group to specific styles was impossible as most yoga expert practice numerous styles of Hatha yoga. However, a yoga practice frequency questionnaire (Appendix B) was given in order to understand our sample demographic (Table 7). Additionally, studies should examine what components of yoga are most beneficial, and what types of patients may receive the greatest benefits from yoga interventions (Hayes & Chase, 2010). Yet, how are we to know the benefits without thoroughly understanding yoga movements? Establishing a motion pattern of common yoga postures, performed by healthy yoga teachers, and comparing to ADL begins to fill the void in literature and support the reported clinical benefits of yoga (Omkar et al., 2011). The motion pattern serves as a reference point in future studies when exploring the benefits within and across subgroups of various ages and pathologies.

There are currently no insurance policies that cover yoga therapy (Hayes & Chase, 2010), but as research continues to uncover the empirical benefits of practicing yoga this may change. With the help of the normative movement as well as future comparison studies, health care providers and fitness professionals will be more informed in prescribing yoga practice, its dosages and possible modifications of treatment to their patients (Cowen & Adams, 2005; Hayes & Chase, 2010).

Based on the research objectives, the results from this study can be applied in various specific areas including; future motion capture research comparing movement patterns of various physical activity as well as in the growing field of yoga therapy and rehabilitation in the treatment of pain, injury and gait function improvement. In establishing the motion pattern of typical yoga movements, we can begin to better understand the suggested benefits of yoga, specifically, the protective and therapeutic mechanisms of yoga movement that make this mind-body activities such an attractive healing practice towards preserving range of motion (ROM) and ADL capacities.

1.6 Limitations of Study

The motion pattern obtained from this study is only applicable to the standing poses selected and for the lower extremity of healthy female yoga teachers.

A few concerns have been proposed with the use of external makers for the collection of motion capture. Skin, clothing and adipose tissue can cause artifact movement (Leardini, Chiari, Della Croce, & Cappozzo, 2005) creating errors in the calculation of joint centers (Reinschmidt, van den Bogert, Nigg, Lundberg, & Murphy, 1997). Additionally, these joint centers are determined by using standard anthropometric data, but personal anatomy can vary greatly. Fortunately, any errors obtained by the generalized body segment parameter algorithm have little influence on the computed joint moments as the relative magnitude of the inertial forces and moment of forces are small compared to the ground reaction force (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004). Moreover, the motion capture system and ground reaction force plates are accepted instrumentation used to create a motion pattern for data analysis. Vicon, the motion capture system used to create this motion pattern, has been shown to create relatively small motion capture error (Dorociak & Cuddeford, 1995; Richards, 1999).

Specific to this study, the Plug-in-Gate (appendix A) marker set has been previously validated for gait studies. Though yoga possesses similarities with gait, in terms of single and double support, its accuracy in yoga motion capture is unknown. Future studies may validate the model in the use of yoga motion research.

1.7 List of Operational Definitions & Abbreviations

Activities of daily living (ADL): Activities such as walking at various speeds, ascending or descending stairs, lifting and object, tying a shoe, and sitting and rising from a chair and squatting.

Angular impulse: Change in angular moment over time, specifically it is the time integral of resultant moment of force acting on a body (N•m•s).

Asana**:** Sanskrit word meaning posture.

Body weight normalized (%BWN): A value expressed as a percentage of an individual's body weight.

Body weight and height normalized (**%BWHT**): A value expressed as a percentage of an individual's body weight, multiplied by their height.

Dhyana: Sanskrit word for meditation.

Dynamic balance: Ability to maintain the body's centre of gravity within the limits of stability.

FoF: Fear of falling.

Ground reaction force (GRF): A single equivalent force equal to the sum of a distribution of forces applied to a surface (Robertson et al., 2004).

Hyperextension: The extension of a joint (knee) beyond the measured baseline. Zero based on static calibration trial.

Linear impulse: Change in moment over time, specifically it is the time integral of resultant moment of force acting on a body (N•s).

Peak joint angles: The maximal and minimal joint angles for a given joint measured by the angle between the two segments that connect the articulation (°).

Peak joint moments: The maximal and minimal moment of force equivalent to the sum of all the moments of the force acting across a joint (N/m).

Plug-in-Gait (PiG): A market set used for motion capture (Appendix B).

Prana**:** Sanskrit word for energy or life force.

Pranayama**:** Sanskrit word meaning breath control or breathing techniques.

Hatha Yoga: The practice of yoga that combines asana, *pranayama* and *dhyana.* It is the most popular form of Yoga in the West.

Range of motion (ROM): The difference between maximal and minimal joint angles, representing the amplitude of movement for a given joint.

Sanskrit: Ancient Indian language and a literary and scholarly language in Buddhism and Jainism.

Sun Salutation: A sequence of 10 yoga postures practiced in synchronization with the breath.

Standard Deviation (SD): A measure of the spread, or dispersion, of the values in a parametric data set standardized to the scale of the unit of measurement of the data.

Standard error of the mean (SE_M): The numeric value that indicates the amount of error in the prediction of a population mean based on a sample.

Step Length: The distance, in the sagittal plane, between the left and right foot in one step and half the stride length.

Stride Length: The distance, in the sagittal plane, between two consecutive steps from the same foot.

Yoga: Sanskrit word meaning to unite, more specifically, unite body, mind and breath.

2 Review of Literature

The review is based on journal articles identified from electronic literature searches using Scopus, SPORTDiscus and PubMed databases for articles pertaining to key words such as, but not limited to: yoga, biomechanics, range of motion (ROM), flexibility, stretching, mind-body, benefits of yoga and yoga injuries. The articles were deemed pertinent if they studied yoga directly or indirectly from 1986-2012. Because of the nature and history of the topic, certain non-peer reviewed works on yoga were cited.

2.1 Review of Yoga

The word yoga is derived from the ancient Indian language's Sanskrit word *yuj*, meaning to unite or to yolk (Hayes & Chase, 2010; Raub, 2002). It is a traditional medical system of the Indian philosophy that believes in the holistic approach (Cowen & Adams, 2005), with origins thought to have beginnings as early as 3000 BCE (Hayes & Chase, 2010). This is to say that, traditionally, health is promoted by seeking balance between physical, spiritual, psychological and social aspects (Cowen & Adams, 2005). In a modern context, yoga promotes health and well-being by integrating the mind, body and breath (Hayes & Chase, 2010). Like many forms of traditional medicine, yoga is a slow-paced activity that has a strong mind-body component (Cowen & Adams, 2005), which implies that the mind can affect the body and the body has an effect on the mind (Ives & Sosnoff, 2000). It is suggested that due to this mind-body component, "complementary and alternative therapies, such as yoga, [are more] therapeutic than traditional exercises" (Schmid et al., 2010). Studies have shown that an 8-week yoga intervention program has significantly improved gait functions in 19 older adults (DiBenedetto et al., 2005). Yoga has also been shown to improve strength and ROM of 10 young adults (Tran et al., 2001) after an 8-week (2x/week) yoga intervention, specifically measurements showing that both isokinetic and isometric muscle strength increased and joint flexibility improved. Possibly the reason why six percent of doctors and therapist are suggesting yoga as a therapeutic tool and 45% of adults surveyed believe that yoga is a beneficial adjunct therapy for traditional medical treatment (Roland et al., 2011). According to Roland et al. (2011), it is clear that the "emerging trend is the recommendation of yoga as an alternative medical therapy."

Yoga is regarded as a meditative exercise (D. Mueller, 2002) and is often misunderstood. It is not a religion, although it is based on ancient Indian philosophies that many consider spiritual (D. Mueller, 2002). Though yoga practice can be physically vigorous, it is also more than the mere exercise of yoga postures (*asana*) that are being taught in the West (Hayes & Chase, 2010). *Asana* were conceived to condition and prepare the body for extended periods of meditation (Hayes & Chase, 2010). Postures normally consist of standing, forward bending, backward bending, twists, hand balances, inversion and restorative postures practiced with the coordination of breath to promote strength, flexibility and balance (Roland et al., 2011). Today, these postures are a means to their own end and are the most popular form of yoga practice in the United States (Hayes & Chase, 2010) regarded as a workout for physical fitness. *Asana* are often accompanied by breathing exercises (*pranayama*) and meditation (*dhyana*) in what is called Hatha yoga (M. Garfinkel & Schumacher, 2000). *Pranayama* is meant to regulate the flow of energy (*prana*) within the body as well as cultivate breath awareness (Hayes & Chase, 2010; Raub, 2002); *dhyana* is practiced to help one concentrate as well as withdraw from the bodily senses (Hayes & Chase, 2010). Though Hatha yoga is the most popular form of yoga practiced in the West, yoga was not meant to serve as only a physical activity. The practice of *asana* is only one part of the eight limbs of yoga (table 1). The different aspects of these eight limbs are emphasized in various proportions in the traditional styles of yoga and are known as *bhakti* (devotion), *karma* (service), *raja* (meditation), *mantra* (chanting), *laya* (abstract thought), *tantra* (ritual), *vedanta* (philosophy) and *hatha* (physical) (Roland et al., 2011). Hatha yoga, the main focus of this study, combines in different ratios and intensity the postures, breathing techniques and meditation and can be divided into styles of Hatha yoga (Table 2).

Table 1 Eight limbs of yoga (Williams et al., 2005)

Limb	**Description**
Yama	Moral injunction
Niyama	Rules for personal conduct
Asana	Postures
Pranayama	Breath control
Pratyahara	Sense withdrawal
Dharana	Concentration and inner awareness
Dhyana	Meditation and devotion
Samadhi	Self-realization or union to the Divine

Table 2 Styles of Popular Hatha yoga (D. Mueller, 2002; Roland et al., 2011)

Style	**Description**
Ananda	Deeply relaxing, practiced for meditation
Anusara	Life-affirming philosophies with alignment
Ashtanga	Rigorous, continuous flow of postures with specific breathing
Bikram	Heated room with strict 26 postures
Integral	Gentle stretch, strengthening and calming the body and mind
Iyengar	Precise and dynamic, use of props to enhance proper alignment. Breathing techniques are not taught until proficiency is reached
Kripalu	Internally directed approach to make poses comfortable, meditation in motion with awareness of breath
Kundalini	Specializes in breathing techniques. Focuses on spine and endocrine system
Restorative	Derived from Iyengar. Postures held for longer. A healing relaxation
Sivananda	Yogic breathing and frequent relaxation. Sun salutation and 12 postures
Viniyoga	Instructor often well versed in therapy and is usually taught privately. Focus on breath

There are many suggested benefits associated to the practice of yoga. It is said that those who practice yoga are more health conscious, in touch with their bodies and often know when something is wrong physically (D. Mueller, 2002). This is to say they can self-regulate and obtain prompt medical attention thereby treating injury or illness sooner. Professional athletes and sports teams practice yoga as a tool to sharpen sports performance (D. Mueller, 2002). Studies have explored the subjective and qualitative benefits of a regular yoga practice. Yoga practitioners in Collin's (1998) study as well as Herrick and Ainsworth (2000) study have noted increased emotional balance, improved awareness and an increase in energy. Other yoga participants have reported enhanced mood (C. Wood, 1993), improved quality of life (Carlson, Speca, Patel, & Goodey, 2004) and elderly participants have reported reduced fatigue (C. Wood, 1993), reduced sleep disturbances and reduction of symptoms of stress (Carlson et al., 2004). Mood alteration, such as depression, is also linked to physiological and biomechanical impairments (Chandler, Duncan, Sanders, & Studenski, 1996). For example, those experiencing a fear of falling (FoF) report an increased sentiment of isolation as well as signs of depression (Chandler et al., 1996). Furthermore, physiological research has shown that the practice of yoga has been associated to improvements in cardio respiratory fitness (Prasad, Ramana, Raju, Reddy, & Murthy, 2001; Raju, Prasad, Venkata, Murthy, & Reddy, 1997; Tran et al., 2001) cardiopulmonary endurance (Tran et al., 2001; Van Puymbroeck, Payne, & Pei-Chun, 2007), increase in forced expiratory volume (Telles, Nagarathna, Nagendra, & Desiraju, 1993), increased endurance, increased vital capacity (Birkel & Edgren, 2000) and other improved physiological measure like lower blood pressure, heart rate and body weight (Murugesan, Govindarajulu, & Bera, 2000; Telles et al., 1993).

Research findings are not consistent with regards to the physiological benefits of yoga practice. For one, in a study conducted by Clay, Lloyd, Walker, Sharp, and Pankey (2005), results suggested that the intensity of Hatha yoga may be insufficient to improve cardiovascular fitness and body composition (Medicine, Franklin, Whaley, Howley, & Balady, 2000). Alternatively, some studies have shown that practicing yoga is equivalent to modern forms of exercise in terms of energy expenditure, but varies between yoga styles (Cowen & Adams, 2007; DiCarlo, Sparling, Hinson, Snow, & Rosskopf, 1995; Rai, Ram, Kant, Madan, & Sharma, 1994; Raju et al., 1986). For example, Ashtanga yoga, which includes numerous repetitions of a sequence of yoga postures called the sun salutation, is a more vigorous form of Hatha yoga and increases the heart rate more so than its gentle yoga counterparts (Cowen & Adams, 2005). In this pilot study, 26 adults were assigned to either a vigorous Ashtanga (n=11) practice or a gentler Hatha (n=15) practice twice a week for 6 weeks, and were asked not to make any changes to their current physical activity habits. No significant differences were found between the groups at baseline. However, significant improvements were reported in diastolic blood pressure, upper body and trunk dynamic muscular strength and endurance, flexibility, perceived stress and health perception in the Ashtanga group, whereas only the strength, flexibility and health perception were significantly improved for the Hatha group (Cowen & Adams, 2005). This study highlights the importance of well describing the intervention's yoga sequence as different styles offer different fitness benefits. In this case, yoga postures are not only utilized to increase flexibility, they improved fitness measurements as well (Cowen & Adams, 2005). There are clear benefits associated to the practice of yoga and continued study of the effects of yoga on biomechanical parameters will contribute to quantitative studies.

2.2 Biomechanics of Yoga

To the author's knowledge, there are merely 6 studies regarding the biomechanics of yoga (Cowen & Adams, 2005; DiBenedetto et al., 2005; Omkar et al., 2011; Schmid et al., 2010; Tran et al., 2001; Westwell et al., 2006). The limited research in the biomechanics of yoga has covered the kinetics and kinematics, including joint moments of force (Omkar et al., 2011; Westwell et al., 2006), flexibility (Cowen & Adams, 2005; Tran et al., 2001), and stride length (DiBenedetto et al., 2005).

2.2.1 Joint Moment of Force

Kinetic variables, such as joint moments of force, are used when biomechanically describing a motion pattern. They can be calculated by inverse dynamics through the combination of motion capture data and ground reaction force (GRF). Moments of force are defined as the product of the joint force (calculated from the GRF) times the perpendicular distance from the force's application point (Robertson, 1997). It represents the net results of muscular, ligament and frictional forces acting to change the angular rotation of a joint (Winters, 1991).

Of the limited studies in the biomechanics of yoga, only 2 studies directly explored the kinetics in yoga practice (Omkar et al., 2011; Westwell et al., 2006). The researchers (Omkar et al., 2011) did not record measurements from participants, instead, created a mathematical model based on rigid body mechanics for each joint during each posture of the sun salutation to calculate the bodyweight and height normalized joint moments (%BWHT).

Figure 2 Cycle representing the 10 postures of the Sun Salutations (image from Omkar et al. (2011))

Omkar et al. (2011) suggested that the model created would be a useful to for predicting the forces and moments that occur during yoga poses and that the poses in the sun salutations present submaximal joint loading when compared to high impact exercise.

Table 3 Variation of the moments (%BWHT) in the sagittal plane on the wrist, elbow, shoulder, hip, knee and ankle joint for one cycle of the Sun Salutation (table from Omkar et al. (2011))

Posture	Wrist	Elbow	Shoulder	Hip	Knee	Ankle
1	0.000	0.000	0.000	0.000	0.000	0.000
2	-0.007	-0.060	-0.077	-0.085	-0.068	-0.077
3	-0.003	-0.017	-0.012	-0.060	-0.060	-0.060
4	0.000	-0.042	-0.042	-0.031	-0.011	-0.016
5	-0.007	-0.007	-0.007	0.174	0.094	0.000
6	-0.250	-0.025	-0.007	0.095	0.072	0.000
7	0.000	-0.011	0.009	0.066	0.172	-0.040
8	0.000	0.024	0.093	-0.163	0.076	0.000
9	-0.007	-0.007	-0.007	0.174	0.094	0.000
10	-0.003	-0.017	-0.012	-0.060	-0.060	-0.060
11	0.000	0.000	0.000	0.000	0.000	0.000

* Positive and negative values were not defined I Omakar et al. (2011) study.

In the second, the researchers' (Westwell et al., 2006) purpose was to better understand the mechanism behind strengthening benefits and injury limitations in specific yoga poses. The 3D motion data of one participant was collected using accepted motion capture methods (Harris, Smith, Medicine, & Conference, 1996) for 5 common standing yoga poses of 1 participant. Measurements included the bodyweight normalized joint moments (Nm/kg) for lower extremity joints in sagittal and frontal plane. It was reported that the joint moments in this pilot study were comparable to walking and running. Specifically, during the practice of five yoga postures (awkward pose, standing back bend, standing bow pose, eagle pose and standing head to knee pose) the joint moments in eagle pose, the subject demonstrated knee extensor moment (1.3 Nm/kg) comparable to running (1.4 Nm/kg) as well as in bow pose there was extensor moment at the hip (1.4 Nm/kg) comparable to running (1.6 Nm/kg). However, the measured impact forces were minimal, suggesting that yoga may be a favorable physical activity in preventing joint deterioration.

Omkar et al. (2011) suggested that producing high joint moments with submaximal joint loading could improve bone remodeling and osteogenesis. Further comparison should be conducted with a larger sample size and various daily activities, such as walking and ascending and descending stairs found in the literature (N. H. Law, 2013; Lee, 2011). The findings from Omkar et al's study cannot be generalized to all populations and standing yoga postures, as there was only one subject and there are hundreds of yoga postures and variations described in yoga training manuals (Coulter, 2001; Kaminoff; M. Kirk & Boon, 2006). Researchers (Omkar et al., 2011; Westwell et al., 2006) highlight the importance of evaluating the joint moments generated during yoga, this conventional human movement analysis allows for comparison of yoga movements with other forms of exercises. This may also have important implications when dealing with specific injuries. In order to successfully compare joint moments, they are normalized for body weight (%BWN) (Westwell et al., 2006) and in some studies they are, normalized by weight and height (%BWHT) where the joint moments are expressed as a percentage of body weight times height (Nordin & Frankel, 2001; Omkar et al., 2011).Though these are interesting findings, these yoga studies did not directly measure the kinetics and kinematics during yoga movements, and those that did lack the appropriate sample size to suggest statistical significance.

2.2.2 Flexibility, Joint Angles and Range of Motion

Joint angle analysis has been used to describe motion pattern in biomechanical analysis of gait (Winters, 1991) and of activities of daily living (Jevsevar, Riley, Hodge, & Krebs, 1993). Measuring joint angles serves as a way to describe the body in space and the amplitude of an individual's movement through ROM. Yoga studies to date have only evaluated participant's pre and post flexibility (Cowen & Adams, 2005; DiBenedetto et al., 2005; Schmid et al., 2010; Tran et al., 2001), but have yet to describe the joint angles throughout yoga movement. This information would help to understand how yoga experts complete the required yoga postures, and in the future, help to determine how novice yoga participants should/can modify the motion pattern to achieve the same pose as well as how the postures must be modified in people with various pathologies.

Yoga intervention programs have been shown to help improving gait function characteristics (DiBenedetto et al., 2005; Tran et al., 2001). In Tran et al.'s (2001) study, the purpose was to determine the effects of Hatha yoga practice on health-related aspects of physical fitness including muscular strength, endurance and flexibility, as after an 8-week Yoga intervention. The strength and ROM of 10 young adults (n= 9 women, n= 1 male, 18-27 years) were measured with an active isokinetic multi-joint dynamometer and goniometer showing that both isokinetic and isometric muscle strength increased and joint flexibility significantly improved when compared to their pre-intervention values.

In a study concerning the hypothesized benefits of yoga to age-related changes in gait function of the elderly (DiBenedetto et al., 2005), researchers found that there was a significant increase in peak hip extension and stride length as well as a trend towards reduced average pelvic tilt during comfortable gait. Kinematic and kinetic data were recorded using Vicon motion capture system and 2 imbedded force plates. Pelvic and joint angles were reported in reference to the zero measured during a comfortable barefoot stance. Participants attended two 90-minute yoga classes per week and practiced 20 minutes of prescribed yoga postures at home on the other days. The frequency and duration of the home practice showed a strong relationship to changes in hip ROM. There was linear response to the frequency of home practice and pelvic tilt. Though there was an increase in stride length, because the motion capture was completed during ambulation pre and post yoga practice, we have no information regarding the mechanisms for this improvement during the yoga movements themselves. By collecting the step length as well as ROM of the lower extremity during the yoga practice, we could help to explain how regular yoga exercise helps to maintain gait capacities compared to previously acquired ADL data (N. H. Law, 2013; Lee, 2011).

In another yoga intervention study on the metabolic cost of Hatha yoga practice, the researchers (Clay et al., 2005) proposed an interesting thought; they speculated that the reduction in passive torque caused by increased flexibility could reduce the joint movement resistance thereby increasing energy efficiency (Terada, Wagatsumal, & Kraemer, 1997). This may explain why the oxygen uptake was so low during yoga performance (Clay et al., 2005). It is possible that an increase in ROM could help reduce the perceived exercise intensity, allowing yoga practitioners to slowly increase their workload (Clay et al., 2005). This would be ideal for those with reduced tolerance to exercise, such as those with FoF.

2.2.3 Gait function, stability and fear of falling (FoF)

The study of gait function is important, as a decrease in gait function and reduction of ROM is associated to fear of falling (FoF) in the elderly (Chandler et al., 1996; DiBenedetto et al., 2005). This is a disabling condition for the elderly who are frail (Chandler et al., 1996; Schmid et al., 2010). It is often associated with depression, functional limitation and gait impairments (Schmid et al., 2010). When an individual suffers with the debilitating FoF, a vicious cycle occurs: there is a decrease in activity, followed by a reduction of participation within their environment thereby leading to further decrease in strength and balance which promote gait function deterioration, finally increasing their risk of fall and increased FoF (Delbaere, Crombez, Vanderstraeten, Willems, & Cambier, 2004; Schmid et al., 2010). The severity of FoF should not be underestimated, as in some cases; these falls can cause injuries limiting an individual's independence and can occasionally lead to death (DiBenedetto et al., 2005). Yoga is an ideal therapy option as it is cost effective (Hagins & Khalsa, 2012), simple to learn and can be practiced, with modification, by most (DiBenedetto et al., 2005; Hagins & Khalsa, 2012).

Many individuals who are affected with FoF are elderly. Older adults have been shown to walk more slowly, with shorter step length, shorter single-stance time, and wider step width (Judge, Ounpuu, & Davis, 1996).These older individuals also tend to generate less power in plantarflexors and hip flexors (Kerrigan, Todd, Della Croce, Lipsitz, & Collins, 1998). These gait indicators have been directly related to the decline in ROM, muscle strength and postural stability (Teixeira-Salmela, Nadeau, McBride, & Olney, 2001).

Yoga has also been shown to improve, by 228%, balance in healthy young adults compared to the control group (C. E. F. Hart & Tracy, 2008) as well as improvements in motor skills such as reduced planning and execution time for complex tasks compared to a physical activity control group (Manjunath & Telles, 2001). In C. E. F. Hart and Tracy (2008) study, balance was measured with a one-legged balance test as force plates were not available for more sophisticated measures of postural stability. It is apparent that there is a relationship between yoga and reduced falls and increased balance (Brown, Koziol, & Lotz, 2008; C. E. F. Hart & Tracy, 2008). There is a meaningful trend towards improved gait functions, strength, flexibility and anthropometric measurements due to yoga practice

(Roland et al., 2011). Rehabilitation therapists may be interested in studying yoga for fall prevention treatments (Schmid et al., 2010). It was suggested by Omkar et al. (2011) to find more biomechanical motion pattern of various yoga postures to help predict the general benefits of yoga.

2.3 Yoga and Injuries

Rehabilitation researchers are interested in exploring yoga as a modality to be used in treatment programs. Researchers have already explored the benefits of yoga practice in those with symptoms of musculoskeletal disorders such as osteoarthritis (M. S. Garfinkel et al., 1994), carpal tunnel syndrome (M. S. Garfinkel et al., 1998), hyperkiphosis (Greendale, McDivit, Carpenter, Seeger, & Mei-Hua, 2002) and low back pain (Galantino et al., 2004) which is of particular importance as low back pain has been deemed the 5th most common reason for doctors visit (L. G. Hart, Deyo, & Cherkin, 1995) and a fourth of Americans experience low back pain in the last 3 months (Deyo, Mirza, & Martin, 2006). In fact, yoga as a treatment for patients with osteoarthritis has reduced pain and improved grip strength (M. S. Garfinkel et al., 1998) as well as increasing isokinetic and isometric muscle strength (Tran et al., 2001) making daily tasks more accessible. As mentioned, yoga intervention programs have been used in gait therapy to reduce fall and FoF (Chandler et al., 1996; DiBenedetto et al., 2005). Any physical activity possible is recommended for older adults as it reduces the risk of premature mortality and preserves functional independence (Paterson, Jones, & Rice, 2007). Caregivers have been recommending yoga as a therapeutic exercise for a wide age range because it is simple to learn and easily practiced anywhere and modified for individuals with different levels of mobility.

The scientific evidence supporting yoga for improved fitness in older adults shows promise (Roland et al., 2011). Further evaluation of the benefits of yoga will help aid health care providers and fitness professionals in counseling their patients about the use of yoga as a health and wellness modality (Cowen & Adams, 2005).

Though yoga is often viewed as a form of therapy and healing, it is important to highlight that the practice of yoga can also cause injury (Bianchi et al., 2004; Fishman et al., 2009; Patel & Parker, 2008). These injuries are generally observed in study of one single subject in the lower limb, specifically the knee. For example, in the case of Patel & Parker's study (2008), there was an isolated incident of a yoga practitioner tearing the lateral collateral ligament during yoga practice. Bianchi et al. (2004) describe in their case study the incident of a 14-year old girl suffering a epiphyseal separation of the distal tibia during the practice of lotus pose during yoga. In a survey where 1336 Yoga teachers responded (Fishman et al., 2009), it was believed by participants that yoga injuries most often occurred due to poor technique or position alignment, previous injuries, excess effort, and insufficient instructions from the yoga instructor. Studying the motion pattern of the yoga movement would help shed light on potential mechanisms of injury and therefore allow for intelligent and informed acceptance of yoga by more of the healthcare community. Specifically, by studying the motion pattern of experienced yoga practitioners, researchers can describe the appropriate way of doing the yoga movements.

3 Methods

The study was conducted in the Human Movement Biomechanics Laboratory, School of Human Kinetics, University of Ottawa (200 Lees avenue, room E020). In this study the biomechanical analysis focused on step length, joint angles, ground reaction force (GRF), joint moments, linear and angular impulse during the movement of the 1) Crescent lunge pose, 2) Warrior II pose 3) Triangle pose, all starting from the same initial position of Downward Dog. These three postures are commonly practiced in many different styles of yoga.

3.1 Participants

Experienced female yoga teachers, matched in age and sex to our previously acquired gait data, were recruited for this study. These teachers were all certified with a Yoga Alliance accredited 200-hour Hatha yoga teacher-training course and have a minimum of 5 years teaching experience. It has been suggested that teachers with several years of experience may be more qualified than certified teachers (D. Mueller, 2002). The decision to include both experienced and certified participants was to obtain true experts in the field. Yoga Alliance is a North American association whose standards are intended to enhance the public perception of yoga teachers as well-trained professionals (Yoga Alliance, 2010). This ensures that all trainings are based on a standard curriculum. The data from this study was compared to ADL data previously collected (N. H. Law, 2013; Lee, 2011) from female participants; therefore we limited our recruitment to female yoga teachers. Participants were matched for sex but not age because participants who would meet the experience criteria would above the age of 25 and according to a previous study; flexibility is significantly reduced in groups of over 45 years of age (Shephard, Berridge, & Montelpare, 1990), therefore the data of 13 certified yoga teachers, aged between 25 and 45, were collected. Although aged matched date was unavailable, comparisons were made with studies examining ADL in healthy adults and the elderly to gauge whether motions patterns possessed any similarities.

Describing a yoga movement starts with pilot data of one single participant

(Westwell et al., 2006) or mathematical models (Omkar et al., 2011). In an effort to increase the study's power, similar to other studies dealing with various biomechanical descriptors (Wang, Flanagan, Song, Greendale, & Salem, 2006), we aimed to recruit 15 participants. Due to lack of interested eligible teachers, only 13 participants were recruited for this study.

The participants for this study were recruited from local yoga studios. In the event that more eligible participants volunteer to be included in the study, participants were accepted on a first come first served basis. Participants were excluded from this study if they report any of the following conditions: neurological diseases or medication that impaired mobility; dementia; cardiovascular disease symptomatic during moderate exercise; poorly controlled hypertension; use of specific medications known to impair balance; and any significant lower limb injury that may affect one's functional ability (i.e. ligament rupture, meniscal tear or tendon injury). By narrowing the inclusion criteria, participants were considered healthy adults making comparison possible in future studies.

3.2 Yoga Movement

The Yoga postures that were studied are the Crescent lunge pose (*Alasana*), Warrior II pose (*Virbradasana II*) and Triangle pose (*Trikonasana*) (Figure 3). To mimic the usual sequencing of a Hatha class, participants were asked to step into these 3 postures from starting from the Downward Dog (*AdhasMukhaSvanasana*) (Figure 4). In Downward Dog, the participant places both hands on the floor either side of a force plate, with feet on the floor with the left foot on a force plate, right foot off and the body in the shape of an upside down "V" (Figure 5). From the Downward Dog, the participant stepped her right foot forward and place it on one of the force plates (toes pointing straight ahead) to come up to the required standing position (Figure 6). Studying the same movement by stepping forward with the left foot would require a lengthy intermission in order to reposition the imbedded force plate placement. In the Crescent lunge pose the participant's hips and shoulders faced front, and her left heel remained off the floor while reaching the arms overhead, intending her torso perpendicular to the floor with the right knee at a 90°. In the Warrior II position the participant's hips and shoulders faced the side, with the left heel on the force plate and the foot pointing 45° to the left and the left leg straight. Her arms should be straight at shoulder height with fingers pointing to the front and back of the collection space. Again, the right knee was intended to be at a 90° and the torso perpendicular to the floor. Finally, in the Triangle pose both the participant's legs were to be straight with the hips and shoulders facing the side and the left heel on the force plate with his foot pointing 45° to the left. In this pose, the arms are straight with fingers pointing up and down while the torso is tilted over the right front leg. In this pose, the intention of this pose is to have the subject's body aligned along a single plane so the body is flat, as if the participant was being compressed between the two panes of a window. Specifically, the left hip is to be over the right hip and the left shoulder directly over the right shoulder.

Figure 3 Sagittal view of Crescent lunge (*left*), Warrior II (*center*) and Triangle (*right*) (www.yogajournal.com).

Figure 4 Sagittal view of Downward Dog, starting position

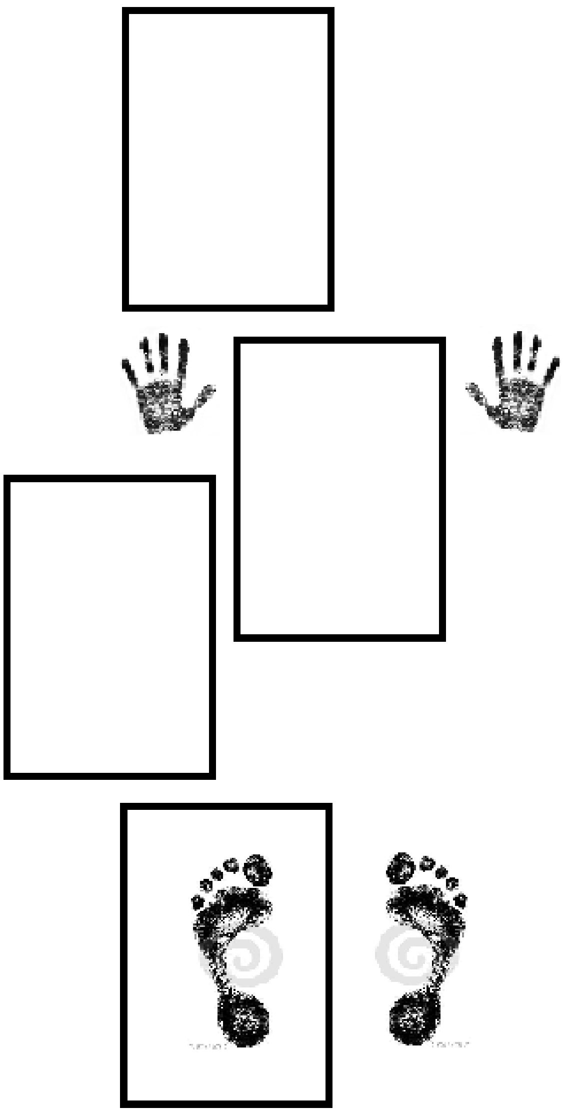

Figure 5 Detailed schematic of force plates, hands and feet positioning in Downward Dog, the starting position

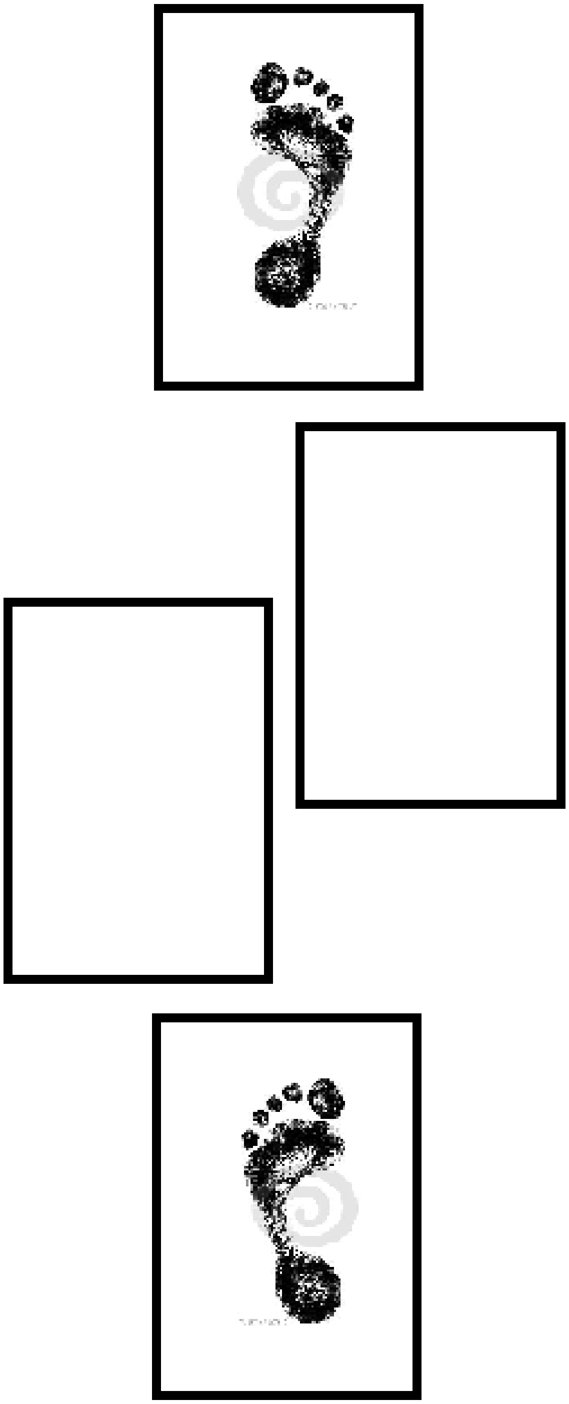

Figure 6 Detailed schematic of force plates and feet in the 3 standing positions; Crescent Lunge, Warrior II and Triangle.

3.3 Instruments

3.3.1 Force Measurements

There were 4 platforms (2 BertecFP 4060-08, Bertec Corporation, Columbus, OH, USA; 2 Kitsler9286AA, Kistler Instruments Corp, Winterhur, Swtz) imbedded into the floor and placed as described in figure 7 within the data collection area. As with all studies in our lab, the frequency of force plates was set at 1000 Hz, to allow for comparison. The three-dimensional (3D) ground reaction forces for each foot during movement were measured to examine the force acting on the each foot and how the weight bearing transfers to overcome gravity from bilateral to unilateral, as well as joint loading of lower limbs.

3.3.2 Motion Capture

The kinematics parameters were obtained using 3D motion capture system while the participants perform yoga postures. Prior to data collection, the ten-camera digital optical motion analysis system (Vicon MX-13, Oxford Metrics, Oxford, UK) with sampling rate of 100 Hz was statically and dynamically calibrated for a volume of 12 m^3 (3.5 x 2.4 x 2.1m) as seen in figure 7. Nexus software (version1.8, Oxford Metrics, Oxford, UK) was used to record and output the 3Dmotion capture data.

To calibrate the system the researcher was firstly conduct a dynamic calibration with the help of a T-shaped wand (240mm) with three reflective markers. In order to allow for the cameras to establish relative position to each other, they were capture at least 7000 frames with a minimum of three markers visible. The static calibration was conducted with an L-shaped frame (ErgoCal 14mm) to establish the origin of the global coordinate system.

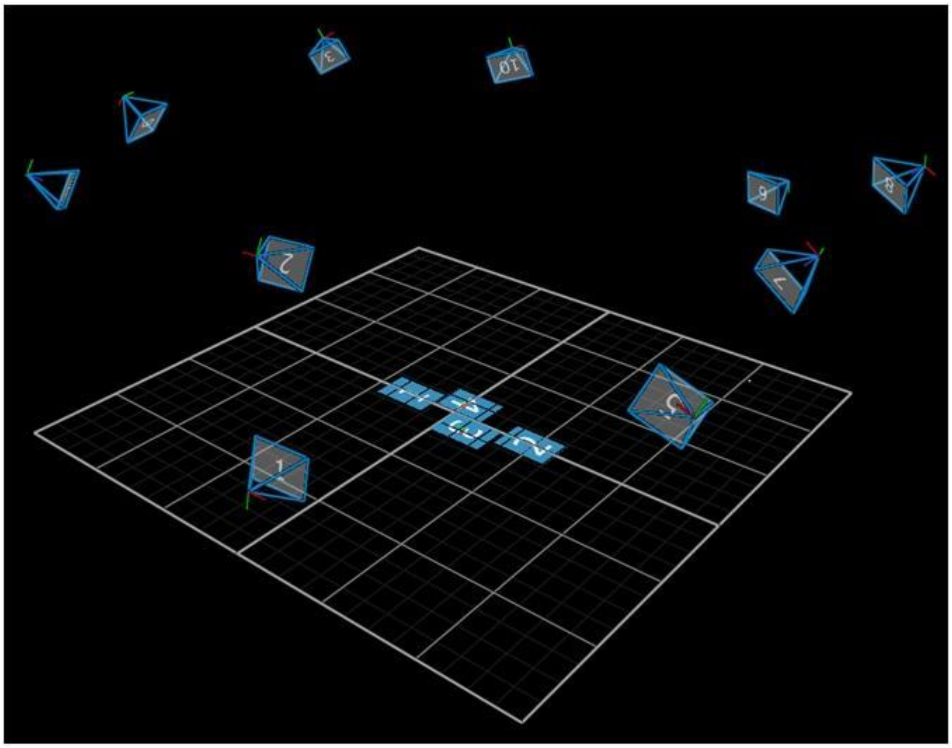

Figure 7 Schematic representation of the imbedded 4 force plates and 10 infrared cameras in the data collection space.

3.4 Participant Preparation Procedures

The participant was firstly asked to read and sign a waiver of informed consent as well as complete a yoga practice frequency questionnaire (Appendix B). After changing into a skin-tight suit, participants were given the opportunity to warm up as they choose (i.e. practice Sun Salutations or other yoga postures). The purpose of the suit is to minimize moving markers caused by loose clothing. This warm up took no longer than 10 minutes, as the researcher had asked the participant to complete their self-practice at home prior to data collection. This ensured that participants were at a comfortable level of mobility.

The researcher collected anthropometric data from the participant, including weight, height, leg length, as well as knee and ankle width. Afterwards, the researcher placed 45 reflective markers (14 mm diameter) on anatomical landmarks of the participant as per the Plug-in-Gait (PiG) market set (Appendix A).

Once all the measurements had been taken and the markers in place, the participant practiced the movements to familiarize themselves with the data collection environment and protocols.

3.5 Testing Protocol and Data Collection

Once the participant was warmed up, one successful static calibration trial was collected, followed by a series of dynamic yoga trials. Data from a static, standing trial with the arms and trunk in a T-shape and feet approximately shoulder-width apart (load evenly distributed on both legs) was collected. The participants were instructed to perform the yoga postures at their natural speed without any reference to the force platforms imbedded in the middle of the testing space for the testing trials. All movements were performed barefoot with the participants wearing appropriate apparel. The participant was asked to practice the following yoga postures: 1) Crescent pose 2) Warrior II pose 3) Triangle pose (Figure 3). The participant was asked to start from Downward dog (Figure 4) and step forward with the right foot into the Crescent lunge and return to Downward dog. Each pose began from Downward dog and the poses were practiced in the same order for each participant; first the Crescent lunge, then Warrior II and finally Triangle pose. Five successful trials for each subject and each posture were recorded for analysis, for a total of 15 dynamic trials, each separated with a break consisting of five deep breaths in Downward dog. Participants will be instructed to take breaks as they desire.

3.6 Data Processing and Analysis

3.6.1 Data Processing

From VICON Nexus software (v1.8), each trial was parsed. The full movement cycle had participants starting in downward dog posture (Figure 4), stepping the right foot off the floor and swinging the leg forward to strike the right foot between the hands on the platform and finishing in the standing postures (Figure 3). The left foot remained on the back force plate throughout the movement cycle, only pivoting as required by the standing posture. Only a portion of the full movement cycle was analyzed as the trials were trimmed to start once the right foot struck the platform (figure 6), when stepping forward from downward dog, and ended once the participant was standing with each foot on separate platforms and motionless in the required posture.

All trials were labeled according to the PiG marker set, gaps in trajectories were filled using a Woltring spline filter (5^{th} order) (G. A. Wood, 1982), and unlabeled trajectories were deleted. The raw kinetic data of the GRF from the force plates was filtered with a 2^{nd} order Butterworth lowpass filter 6Hz. The kinetic and kinematic data were modeled to compute the required variables with Vicon Nexus (v1.8) and each trial was time normalized then averaged within participant with MatLab (MathWorks, Natick, USA). Data was exported in ASCII file format to Excel (Microsoft, Washington, USA).

Measurement of the foot strike was obtained by visually inspecting the force vector emitted from the force plate and position of the virtual marker. For each successful trial, one with all markers present, feet were fully placed on the force plates and deemed to feel normal and successful by the participant, the motion cycle was normalized on a time basis of 100% to mitigate the affects of the varying speed of each individual. The profiles of the five successful normalized trials were averaged to obtain an ensemble average for each participant. These values were then averaged to obtain a group mean, as well as the standard deviation (SD).

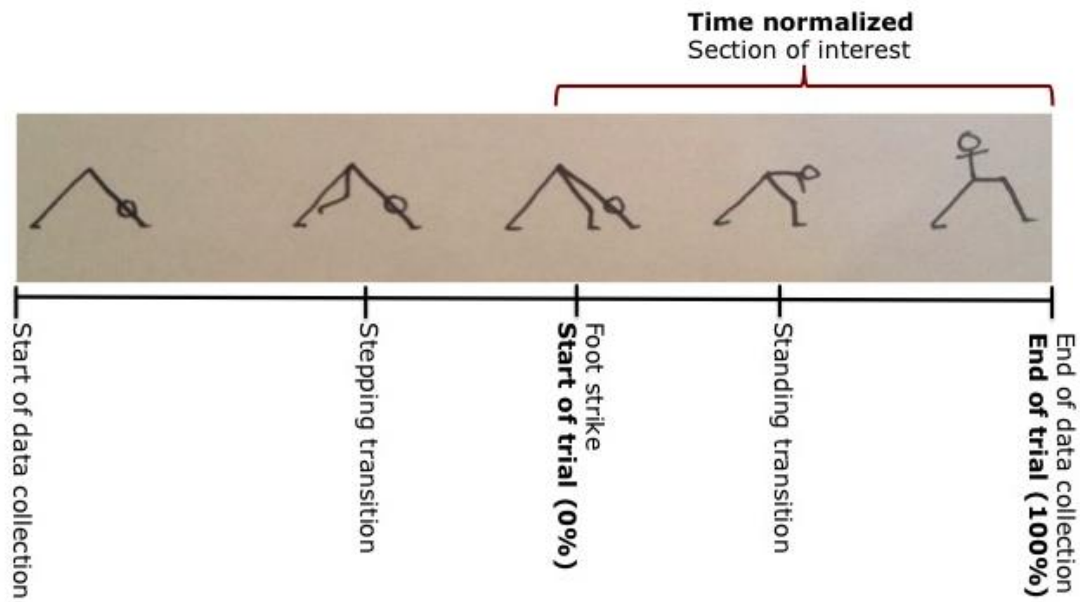

Figure 8 Image describing data collection trial events and time-normalized section of interest.

The kinetic and kinematic data for both right and left leg was collected but only the right leg data was analyzed, as only the right side was in motion leading into the yoga posture. The step length was measured from left to right heel in the anterior-posterior direction.

The 3D kinematic measurements of the lower extremity were processed with Vicon Nexus software (v1.8). The angles in the sagittal and frontal planes were obtained by calculations derived from the PiG model that predicts joint centres of the hip, knee, and ankle in Vicon Nexus (v1.8) and exported in ASCII file format to Excel (Microsoft, Washington, USA) to find the maximum and a minimum angle during each trial. The ROM was determined by calculating the range between the maximum and minimum for each trial. In order to reflect the full of ROM experienced during a yoga practice and the ADL practice, a new metric, $ROM_{practice}$, was calculated. $ROM_{practice}$, is the largest difference between the maximum and minimum angle of a join regardless of the pose and shows the full ROM experienced by the joint amongst the participants throughout all movements. For example, the maximal knee joint angle could be found moving to the lunge pose while the minimal in moving to the triangle pose, the difference between these two values would represent the ROM of the practice of yoga and ADL as a whole, instead of an average.

The computed data were also used to calculate the average GRF normalized by the body mass (N/kg) of each participant by isolating the force along the longitudinal axis (z) and dividing it by the participants body mass (N). The linear impulse was obtained by calculating the integral based on the body weight and time normalized GRF and expressed as the sum GRF (N/kg) of one movement cycle.

Inverse dynamic model was applied to calculate the kinetic parameters. The GRF data and the 3D location of the virtual marker collected by Vicon Nexus (v1.8) were used to calculate the joint moments of force for the hip, knee and ankle. By using MatLab (MathWorks, Natick, USA), a maximum joint moment value for each articulation during the movement was obtained. Joint moments were normalized to body mass to allow for comparison between subjects and to previous studies.

The angular impulse was obtained by calculating the integral of the joint moment of each joint in both the sagittal and frontal plane in one movement cycle. It is expressed as a sum of the total angular impulse (Nm/kg) of one movement cycle. In order to better understand the contribution of each joint of hip, knee and ankle to one cycle movement in frontal and sagittal plane in each yoga posture the percentage of each joint angular impulse to (%) to total angular impulse of lower limb was analyzed and presented in a chart.

The ADL data for comparison with this study data was obtained from our previous studied at our lab. Therefore the ADL data (N. H. Law, 2013; Lee, 2011) was processed similarly to the data processing described above (table 10 and 20).

3.6.2 Statistical Analysis

The dependent and independent variables in this study are listed in table 4 and 5. For comparison between biomechanics yoga and ADL, the ADL data obtained from previous studied at our lab was used (Table 6) (N. H. Law, 2013; Lee, 2011). The mean and SD of the measures of the variables for comparison during ADL are presented tables 10 and 20.

Table 4 Independent variables

Category	Levels
Yoga movement	Crescent lunge (*Alasana*) Warrior II (*Virabhadrasana II*) Triangle (*UtthitaTrikonasana*)
Activity of daily living movements (ADL)	Walking Stair ascent Stair descent

Table 5 Dependent variables for the hip, knee and ankle in the sagittal and frontal plane

Category	Description (unit)
Spatial	Step length (m)
Kinematic	Joint range of motion (°)
	Peak joint angle (°)
Kinetic	Peak ground reaction force (N/kg)
	Linear impulse (N•s)
	Peak joint moment (Nm/kg)
	Angular impulse (N•m•s)

Table 6 Data sources for peak joint angles and peak joint moments of the lower limbs in ADL

	Walking	**Stair ascent & descent**
Researchers	Soul Lee & Jing Xian Li	Nok-Hin Law & Jing Xian Li
Location of study	Human Movements Biomechanics Laboratory, University of Ottawa	Human Movements Biomechanics Laboratory, University of Ottawa
Studied population	Women aged 18 to 30 years n = 15	Women aged 50 to 75 years n = 20
Studied variables	Peak joint angles and peak joint moments of the hip, knee and ankle in the sagittal and frontal plane	Peak joint angles and peak joint moments of the hip, knee and ankle in the sagittal and frontal plane
Testing condition	Walking with and without unilateral load (purse) with various weights	Walking up and down stairs
Research outcome	Master's thesis Paper published (*Journal of the American Podiatric Medical Association*): Effects of high-heeled shoes and asymmetrical load carriage on lower extremity kinematics during walking in young women Paper accepted for publication (*Journal of the American Podiatric Medical Association*): Effect of asymmetrical Load Carrying on joints kinetics of lower extremity during walking in high-heeled shoes in young women.	Master's thesis Paper under review for publication (*Human Movement Science*): Kinematics and kinetics analysis of the lower extremity of normal weight, overweight, and obese individuals during stair ascent and descent.

* Table based on N. H. Law (2013) and Lee (2011) works.

Descriptive statistics obtained for all variables were analyzed using Statistical Package for Social Sciences (SPSS) version 22.0 software (SPSS Inc., Chicago, IL, USA) for Windows.

Prior to performing any statistical analysis for comparison, the data were compiled to obtain descriptive statistics. The data were visually inspected for any outliers and further analyzed showing the kinetic and kinematic data collected was slightly skewed, kurtotic, and did not pass the Shapiro-Wilk's test for homogeneity of variance. Therefore the data are not normally distributed. Furthermore, the Levene's test of equality for ranked data was not satisfied. As such, this ruled out the proposed use of the MANOVA and as well as its non-parametric counterpart, the Krushkal-Wallis test. Therefore the comparison analysis was limited to examining the percentage of difference (Perry, 1992).

The mean and standard deviation for each variable is presented in a series of graphs and tables. Specifically, the step length (m) was expressed in a table. The kinematic data, the peak joint angles (°) and ROM, were presented in a table and figure. The kinetic data, the GRF (N/kg), the total linear impulse (N/kg), the joint moments (Nm/kg), and the total angular impulse (Nm/kg) of each joint as a percentage of the total angular impulse (%) of the lower limb joints were all presented in a variety of tables and figures. These figures demonstrate the kinematic and kinetic characteristics of the three yoga movements.

The means for yoga movements of the joint angles (°) and joint moments (Nm/kg) were then compared to the ADL data by calculating the percentage of change. The percentage of change was calculated in Excel (Microsoft, Washington, USA) by calculating the difference of the compared variable between the yoga and ADL value and then dividing by the ADL value multiplied by 100. These values were tabulated and presented in a series of tables. The values obtained for the percentage of change was deemed noteworthy when it was above 10% and especially highlighted if it was above 1000%.

$$\frac{ADL\ data - Yoga\ data}{ADL\ data} \times 100 = \%\ of\ change$$

Further statistical analysis was conducted to examine the effect size, Cohen's d, using the computed Cohen's d

$$d = \frac{m_{ADL} - m_{Yoga}}{\sqrt{\frac{(n_1-1)s_1^2+(n_z-1)s_2^2}{n_1+n_2}}}$$

to determine what proportion of changes were attributed to treatment effects and if the results are practically significant. This statistical method may be more useful at determining practical significance (R. E. Kirk, 2007), regardless of the scale of the study and sample size, as the corrected p value for the comparison is very small for the sample chosen. It is commonly accepted that there is a small effect size when d=0.20, medium when d=0.50 and large d>0.80 (Cohen, 1992). These results were presented in a series of tables.

4 Results

The data of the measures is presented in means and standard deviation (SD).

Table 7 Demographic detailing the yoga participant's age (years), their teaching experience (years), body mass (kg), and body height (cm) as well as those for ADL participant comparison.

Participants	**Yoga (n = 13)**	**ADL (walking n = 12)** (Lee, 2011)	**ADL (stair n = 19)** (N. H. Law, 2013)
Age (years)	33.1 (± 5.40)	24.7 (± 3.5)	61.4 (± 6.1)
Teaching (years)	5.5 (± 1.05)	--	--
Body Mass (kg)	63.3 (± 10.4)	55.0 (± 6.7)	59.5 (± 7.8)
Body Height (cm)	163.1 (± 5.6)	162.2 (± 3.9)	163.8 (± 7.9)

4.1 Spatial and Kinematic

4.1.1 Step length

The step length (m) measured for yoga practitioners was calculated for all three yoga movements. The longest step length was 1.98m for the Lunge, 1.51m for the Warrior II, and shortest for the Triangle at 1.43m (Table 8).

Table 8 Mean and standard deviation of the step length (m) during individual and average of combined yoga movements.

	Step Length (m)	SD (±)
Yoga average	1.64	0.30
Lunge	1.98	0.37
Warrior II	1.51	0.81
Triangle	1.43	0.84

When compared to walking, step length is clearly largest in yoga movements, especially in the Lunge (Figure 9).

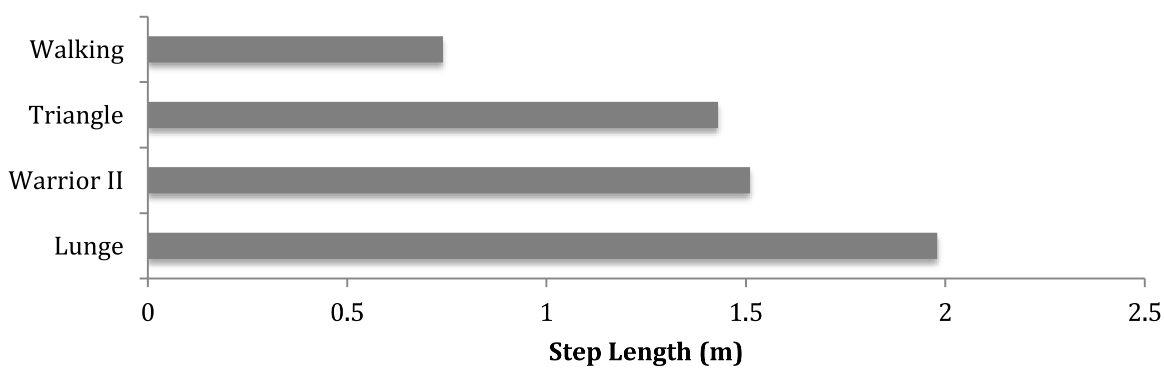

Figure 9 Mean step length (m) during individual yoga movements and walking.

4.1.2 Joint Angles

The three yoga movements begin in the same initial yoga posture and as such begin at the same joint angle in all three joints, the hip, the knee, and ankle complex, in frontal and sagittal planes as illustrated in figures 10 and 11. The $ROM_{practice}$ for yoga movements was 90.5° for the hip, 83.3° for the knee, and 48.7° for the ankle in the sagittal plane and 54.8° for the hip, 44.9° for the knee, and 4.8° for the ankle in the frontal plane. When analyzing the individual yoga movements we observe that the ROM is largest in the sagittal plane in the hip (90.5°), knee (68.8°), and ankle (46.4°) and in the frontal plane in the hip (54.8°), knee (42.4°), and ankle (4.8°) in Triangle. Therefore, moving into Triangle pose requires the most ROM for all three joints in both planes.

A 10% difference was present when comparing the $ROM_{practice}$ and joint angle average peaks for the yoga movements to those of ADL. When comparing the $ROM_{practice}$ for the yoga movements to ADL, the $ROM_{practice}$ in yoga was greater for the sagittal hip, frontal hip, and frontal knee were greater, and smaller in the sagittal knee, sagittal ankle, and frontal ankle (Table 9-14).

Sagittal plane:

Hip joint

In the beginning of the movement cycle, the hip joint flexion angle reaches its maximum value at approximately 120° and remain in flexion throughout the entire movement cycle for all yoga movements. The flexion reduces to the minimal values of 83.3° for the Lunge, and 43.8° for the Warrior II and 31.3° for the Triangle (Figure 10a and Table 9). The largest ROM for the hip in the sagittal plane was 90.5° during the Triangle pose, followed by 77.0° during the Warrior II and 38.0° in the Lunge.

The maximal and minimal values used to calculate the $ROM_{practice}$ for yoga movement both came from Triangle pose therefore, as a whole, the movement of the hip in the sagittal plane is at its maximum during Triangle pose for a $ROM_{practice}$ of 90.5°.

When compared to the joint angles in ADL, there is a notable change between maximum, minimum and $ROM_{practice}$. This change is most distinguished when considering the minimal value where yoga hip angle minimum is 1715.54% larger than that of ADL. There was no notable change (0.40%) when comparing the ROM of the hip in Warrior II to $ROM_{practice}$ of ADL.

Knee joint

The flexion in the knee joint begins much the same at approximately 30° for all three poses and peak between 60° and 75° for all three poses in the first quarter of the movement cycle. There is little change in the knee flexion throughout the movement for the Lunge and Warrior II, however, notice 9.5° of knee extension in Triangle pose (Figure 10b and Table 9).

The yoga $ROM_{practice}$ was obtained by calculating the difference between the maximal knee flexion angle value from the Lunge position (73.8°) and the minimal knee extension angle value from the Triangle position (9.5°) resulting in a yoga $ROM_{practice}$ of 83.3°.

When compared to joint angles in ADL, there is a notable change in most comparison. The changes are most distinguished (300-600% change) when considering the minimal knee angle values. There is no noteworthy change when comparing yoga average minimal knee joint angles to those of walking (7.17%), no noteworthy change when comparing yoga $ROM_{practice}$ of the knee to that of ROM during stair ascent (8.47%), and no noteworthy change when comparing knee maximum from triangle to walking (5.08%).

Ankle joint

The ankle angle begins similarly for all three poses and peaks between 6° and 9° of dorsiflexion in the first quarter of the movement cycle. The range of motion in the ankle remains similar throughout the movement cycle for the Lunge and Warrior II, however the ankle moves into deep plantarflexion at 38.3° in Triangle pose (Figure 10c and Table 9).

The largest ankle angle peaks for all yoga movements are found in the sagittal ankle joint in the Lunge 9.1° dorsiflexion and the Triangle pose 38.3° plantarflexion with a $ROM_{practice}$ or 48.7° which is notably smaller than ADL $ROM_{practice}$.

The ankle angles during yoga practice are all notably changed (>10% change) when compared to those of ADL but none are extremely noteworthy (<100% change) with the exception of walking compared to maximum ankle angle during average yoga movement (4.57%) the Lunge (5.55%) and Warrior II (8.07%). Walking maximal ankle angle is only notably changed when compared to the practice of Triangle pose (16. 23%).

Frontal

Hip joint

The abduction of the hip begins similarly for all three yoga postures (Figure 11a) at approximately 5° and remains relatively neutral in the Lunge pose for a ROM of 8.2° (Table 9). The peak hip abduction angle is greater in the Warrior II (55.3°) and the Triangle (60.4°) thereby creating larger ROM in the Warrior II (49.7°) and Triangle pose (54.8°).

The $ROM_{practice}$, 54.8°, is obtained from the maximal and minimal frontal hip angles of the Triangle pose and is greater than the hip ROM in any of the ADL movements (Table 9 and 10).

All the percentages of change in hip angles of frontal plane between yoga and ADL (Table 11-14), are greater than 10%, and most also being greater than 100%. They are especially distinguished when comparing the minimal hip adduction of yoga movements to walking (11244.54% change), minimal hip adduction of Warrior II to that of ADL average

(1029.27% change) and to walking (15084.57% change).

Knee joint

All three postures start with the knee in slight abduction at approximately 40° (Figure 11b). The Lunge and Warrior II slightly reduce this abduction angle throughout the movement cycle to 17.6° and 24.2° and the knee returns close to baseline in slight adduction at 1.9° (Table 9). The larger abduction angles of the knee are present primarily in the first quarter of the movement cycle, which coincides with the flexion of the knee. Once the knee is at its maximum angle in the sagittal plane (approximately 70°) the subjects begin to adjust the knee inward, reducing the abduction from 42.9° to 17.6° for lunge, 42.0° to 24.2° for warrior II, and 40.4° to 1.9° of adduction for triangle. But in Triangle the leg is also fully extended in the sagittal plane beyond its baseline to 9.5° of extension.

The largest ROM for the knee in the frontal plane was found during the practice of Triangle pose (42.4°) and in ADL movements was during stair ascent (16.0°). The $ROM_{practice}$ for the knee was obtained from the maximal knee angle in the Lunge and the minimal knee angle in the Triangle for a $ROM_{practice}$ of 44.9°.

This $ROM_{practice}$ is greater in yoga practice (44.9°) than ADL movements (24.6°) by 82.52%. The change is noteworthy in all comparison except when comparing knee ROM in the Lunge (25.4°) to the $ROM_{practice}$ (24.6°) of ADL with a change of only 3.04%. The most noteworthy changes are shown when comparing yoga average knee minimal angles to stair ascent (4088.42%) and to stair descent (1570.80%), comparing Lunge minimal angles to stair ascent (5450.27%) and to stair descent (2049.02%), as well as the minimal knee angles during Warrior II to those of stair ascent (7526.13%) and stair descent (2777.98%).

Ankle joint

In all three movements the ankle joint remain in slight abduction, or eversion of the foot, ranging between 1.8° for Triangle ankle angle minimum to 6.6° in Warrior II ankle angle maximum (Table 9). The angle patterns in Figure 11b and 8c can be visually inspected to notice that the abduction of the foot coincides with greater abduction of the knee.

The $ROM_{practice}$ during yoga movements was obtained by calculating the difference between the maximal and minimal ankle angle values during Triangle pose (4.8°), meaning the ROM of yoga movements is wholly achieved by practicing Triangle pose.

The $ROM_{practice}$ of ADL (11.3°) was notably larger (57.24%) than that of yoga movements (4.8°). The average minimal ankle angle for ADL is 1.4° of adduction, or inversion of the foot. This represents 246.79% of difference when compared to the minimal ankle angle for yoga movements (Table 11). It is interesting to note that all difference between yoga and ADL were deemed noteworthy (>10% change). However, none of the differences were deemed extremely noteworthy (>1000%) (Table 11-16).

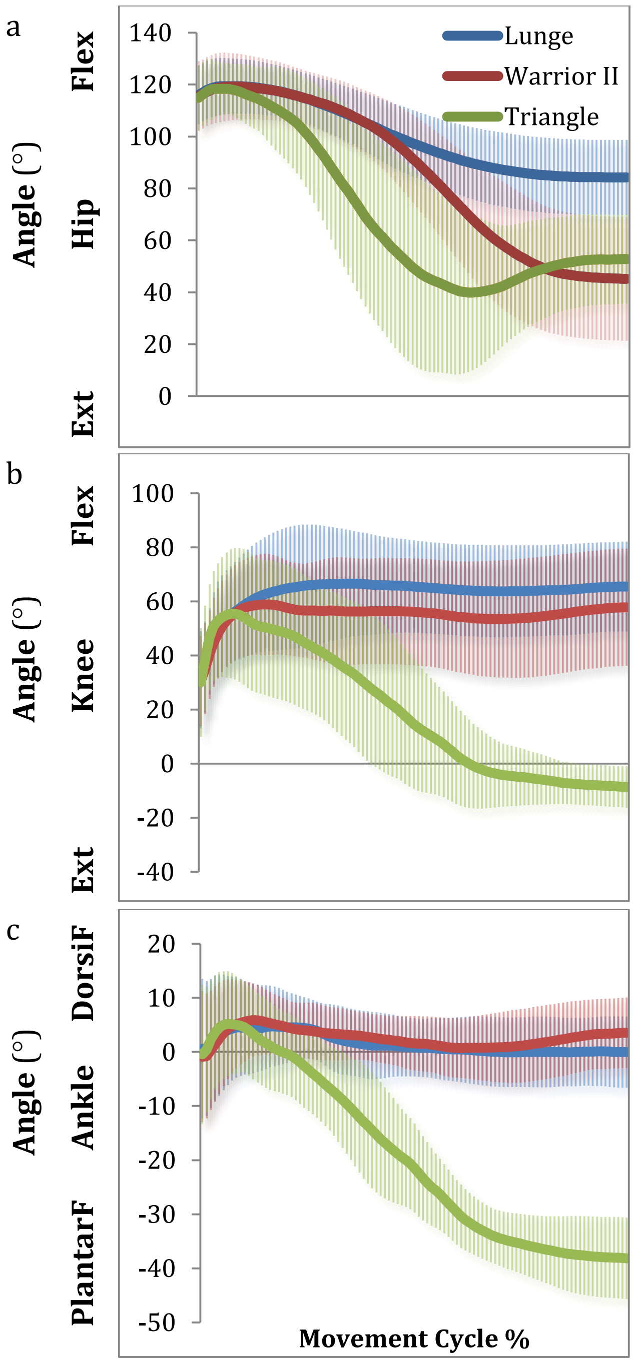

Figure 10 The joint angles (°) during lunge (blue), Warrior II (red), and Triangle (green) in (a) hip flexion and extension (b) knee flexion and extension (c) ankle plantar flexion and dorsi flexion. Vertical lines represet standard deviation.

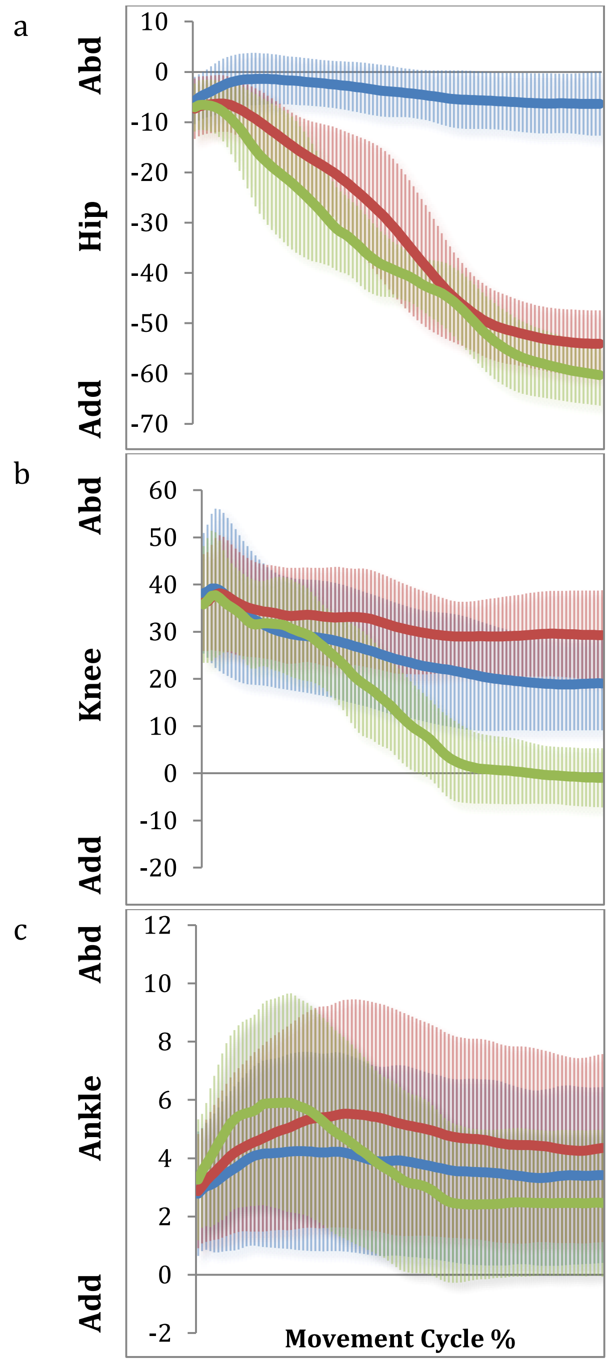

Figure 11 The joint angles (°)during lunge (blue), Warrior II (red), and Triangle (green) (a) hip adduction and abduction (b) knee valgus and varus (c) ankle adduction and abduction. Vertical lines represet standard deviation.

Table 9 Mean and standard deviation for peak joint angles and range of motion (°) in the sagittal and frontal plane during individual and combined average of yoga movements (Lunge [n=13], Warrior II [n=12], and Triangle [n=12s]).

Activity	Movement	Direction	Hip	SD	Knee	SD	Ankle	SD
Yoga Averages	Flex/Ext	Max	121.3	0.5	66.9	7.3	9.2	1.2
		Min	52.8	27.2	17.1	23.1	-17.0	18.4
		ROM	90.5		83.3		48.7	
	Abd/Add	Max	-3.7	3.2	41.8	1.3	5.8	0.9
		Min	-41.3	28.7	13.3	13.6	2.1	0.3
		ROM	54.8		44.9		4.8	
Lunge	Flex/Ext	Max	121.3	10.4	73.8	17.6	9.1	7.3
		Min	83.3	14.7	31.0	18.0	-6.6	8.4
		ROM	38.0	13.1	42.7	15.3	15.7	7.2
	Abd/Add	Max	-0.1	5.1	42.9	15.0	4.8	2.9
		Min	-8.3	5.3	17.6	8.9	2.1	2.5
		ROM	8.2	3.8	25.3	12.7	2.8	1.3
Warrior II	Flex/Ext	Max	120.8	12.6	67.7	19.9	10.4	5.4
		Min	43.8	23.9	29.9	15.7	-6.3	7.7
		ROM	77.0	24.3	37.8	14.3	16.7	6.5
	Abd/Add	Max	-5.5	6.0	42.0	8.9	6.0	3.2
		Min	-55.3	6.4	24.2	9.2	2.4	2.6
		ROM	49.7	7.5	17.8	9.9	3.6	1.5
Triangle	Flex/Ext	Max	121.8	11.8	59.2	23.5	8.1	9.2
		Min	31.3	22.8	-9.5	6.1	-38.3	7.5
		ROM	90.5	22.9	68.8	23.1	46.4	11.3
	Abd/Add	Max	-5.5	5.5	40.4	12.2	6.6	3.0
		Min	-60.3	6.1	-1.9	5.4	1.8	2.4
		ROM	54.8	6.5	42.4	12.8	4.8	1.7

Note: Positive values indicate flexion and abduction and negative values indicates extension and adduction.

Table 10 Mean and standard deviation for peak joint angles and range of motion (°) in the sagittal and frontal plane during individual and combined average of ADL movements (walking [n=12], stair Ascent [n=19], and stair descent [n=19]).

Activity	Movement	Direction	Hip	SD	Knee	SD	Ankle	SD
ADL Averages	Flex/Ext	Max	49.2	16.5	85.1	19.7	18.1	13.0
		Min	2.9	10.6	5.4	1.3	-24.5	3.4
		ROM	77.3		93.3		59.9	
	Abd/Add	Max	10.6	7.9	9.3	5.3	7.0	2.6
		Min	-4.9	3.9	-3.5	5.6	-1.4	0.7
		ROM	27.0		24.6		11.3	
Walking	Flex/Ext	Max	38.6	4.3	62.4	10.2	9.7	5.1
		Min	-9.2	3.5	4.3	2.0	-26.1	6.7
		ROM	47.7		58.1		35.8	
	Abd/Add	Max	19.7	3.5	4.1	0.5	9.4	2.6
		Min	-0.4	5.1	-10.0	5.8	-1.9	0.8
		ROM	20.1		14.1		11.3	
Ascending Stairs	Flex/Ext	Max	68.2	6.4	97.6	7.5	11.7	4.2
		Min	7.1	4.6	6.8	4.5	-20.7	5.5
		ROM	62.0	4.1	91.0	8.2	33.3	5.1
	Abd/Add	Max	6.6	4.6	14.6	13.4	4.2	3.9
		Min	-7.3	2.4	0.3	5.6	-1.7	1.7
		ROM	14.1	3.7	16.0	9.2	8.0	3.4
Descending Stairs	Flex/Ext	Max	40.9	7.5	95.3	5.4	33.1	5.9
		Min	10.8	6.4	5.0	3.4	-26.8	7.4
		ROM	30.1	3.1	93.1	3.5	61.7	6.0
	Abd/Add	Max	5.7	3.1	9.2	15.6	7.4	6.9
		Min	-7.0	3.3	-0.9	4.3	-0.6	1.2
		ROM	13.5	3.8	13.3	11.0	13.4	4.5

* Table adapted from work previously done in our laboratory (N. H. Law, 2013; Lee, 2011)

Note: Positive values indicate flexion and abduction and negative values indicates extension and adduction.

Table 11 Percentage of change (%) comparing joint angles of yoga averages to ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Yoga Averages	Flex/Ext	Max	Hip	146.44	214.37	77.84	196.79
			Knee	21.39	7.17*	31.46	29.78
			Ankle	49.22	4.57*	21.26	72.15
		Min	Hip	1715.54†	676.87	641.14	391.01
			Knee	220.15	299.48	152.99	243.10
			Ankle	30.54	34.77	17.47	36.49
		ROM	Hip	16.98	89.57	46.05	200.33
			Knee	10.76	43.26	8.47*	10.55
			Ankle	18.66	36.16	46.40	21.06
	Abd/Add	Max	Hip	135.00	118.91	156.69	165.84
			Knee	349.73	924.20	186.43	353.93
			Ankle	16.62	37.70	39.48	21.61
		Min	Hip	743.69	11244.54†	466.37	487.53
			Knee	476.48	232.85	4088.42†	1570.80†
			Ankle	246.79	209.48	221.50	425.37
		ROM	Hip	103.01	173.10	287.79	305.83
			Knee	82.52	218.75	180.91	236.26
			Ankle	57.24	57.24	39.66	64.11

* Percentage of change < 10% - No notable change

† Percentage of change > 1000% - Very notable changes

Table 12 Percentage of change (%) comparing joint angles of Lunge to ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Lunge	Flex/Ext	Max	Hip	146.42	214.35	77.83	196.76
			Knee	13.33	18.16	24.43	22.58
			Ankle	49.74	5.55*	22.06	72.43
		Min	Hip	2765.00†	1010.33†	1069.54†	674.84
			Knee	479.41	622.99	357.86	520.95
			Ankle	73.27	74.90	68.24	75.56
		ROM	Hip	50.90	20.43	38.69	26.06
			Knee	54.21	26.50	53.04	54.10
			Ankle	73.83	56.19	52.90	74.60
	Abd/Add	Max	Hip	100.73	100.39	101.18	101.37
			Knee	362.16	952.50	194.34	366.47
			Ankle	31.10	48.52	15.25	35.23
		Min	Hip	68.86	2170.58†	13.36	17.59
			Knee	598.89	276.04	5450.27†	2049.02†
			Ankle	244.45	207.74	219.57	420.20
		ROM	Hip	69.67	59.19	42.06	39.36
			Knee	3.04*	79.95	58.59	89.84
			Ankle	75.54	75.54	65.48	79.47

* Percentage of change < 10% - No notable change

† Percentage of change > 1000% - Very notable changes

Table 13 Percentage of change (%) comparing joint angles of Warrior II to ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Warrior II	Flex/Ext	Max	Hip	145.47	213.14	77.15	195.62
			Knee	20.46	8.44*	30.65	28.95
			Ankle	42.50	8.07*	10.83	68.46
		Min	Hip	1405.49†	578.36	514.57	307.16
			Knee	458.74	597.19	341.52	498.80
			Ankle	74.38	75.94	69.56	76.58
		ROM	Hip	0.40*	61.41	24.35	155.71
			Knee	59.53	35.03	58.49	59.44
			Ankle	72.10	53.29	49.77	72.92
	Abd/Add	Max	Hip	152.14	128.17	184.45	198.08
			Knee	351.98	929.33	187.86	356.20
			Ankle	13.66	35.49	44.43	18.83
		Min	Hip	1029.27†	15084.57†	658.08	686.40
			Knee	785.48	341.89	7526.13†	2777.98†
			Ankle	268.59	225.74	239.54	473.69
		ROM	Hip	84.22	147.82	251.89	268.25
			Knee	27.58	26.48	11.46	33.42
			Ankle	67.78	67.78	54.52	72.96

* Percentage of change < 10% - No notable change

† Percentage of change > 1000% - Very notable changes

Table 14 Percentage of change (%) comparing joint angles of Triangle to ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Triangle	Flex/Ext	Max	Hip	147.43	215.63	78.55	197.97
			Knee	30.38	5.08*	39.30	37.81
			Ankle	55.42	16.23	-30.88	75.55
		Min	Hip	976.15	441.94	339.30	191.04
			Knee	277.71	321.74	240.43	290.45
			Ankle	56.03	46.54	85.39	42.67
		ROM	Hip	16.98	89.57	46.05	200.33
			Knee	26.31	18.30	24.42	26.14
			Ankle	22.58	29.61	39.35	24.86
	Abd/Add	Max	Hip	152.13	128.16	184.43	198.06
			Knee	335.05	890.77	177.08	339.11
			Ankle	5.10*	29.10	58.75	10.78
		Min	Hip	1132.93†	16478.48†	727.67	758.59
			Knee	45.07	80.62	711.12	114.60
			Ankle	227.32	194.96	205.38	382.21
		ROM	Hip	103.02	173.11	287.80	305.84
			Knee	72.28	200.86	165.14	217.39
			Ankle	57.24	57.24	39.66	64.11

* Percentage of change < 10% - No notable change

† Percentage of change > 1000% - Very notable changes

Table 15 Effect size (r) comparing joint angles of the Yoga averages to those to ADL averages and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Yoga Averages	Sagittal	Max	Hip	6.18†	26.85†	11.62†	15.03†
			Knee	10.36†	0.50	4.16†	4.41†
			Ankle	0.97†	0.12*	0.81†	5.60†
		Min	Hip	2.42†	7.03†	2.35†	2.13†
			Knee	0.72	0.78	0.62	0.88†
			Ankle	0.57	5.99†	0.27	0.70
		ROM	Hip	--	--	--	--
			Knee	--	--	--	--
			Ankle	--	--	--	--
	Frontal	Max	Hip	2.40†	7.03†	2.62†	2.99†
			Knee	8.50†	39.22†	10.43†	2.95†
			Ankle	0.59	1.79†	0.58	0.33
		Min	Hip	1.78†	1.98†	1.67†	1.68†
			Knee	1.62†	12.42†	1.25†	1.41†
			Ankle	6.68†	6.44†	3.18†	3.13†
		ROM	Hip	--	--	--	--
			Knee	--	--	--	--
			Ankle	--	--	--	--

* Effect size ≈ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 16 Effect size (r) comparing joint angles of the Lunge to those to ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Lunge	Sagittal	Max	Hip	5.23†	10.36†	6.12†	8.84†
			Knee	0.61	0.79	1.77†	1.65†
			Ankle	0.86†	0.09*	0.43	3.61†
		Min	Hip	6.27†	8.66†	7.00†	6.40†
			Knee	2.01†	2.09†	1.85†	2.01†
			Ankle	2.80†	2.58†	1.99†	2.55†
		ROM	Hip	--	--	2.48†	0.83†
			Knee	--	--	3.92†	4.53†
			Ankle	--	--	2.82†	6.93†
	Frontal	Max	Hip	1.62†	4.54†	1.38†	1.36†
			Knee	3.00†	3.67†	2.00†	2.21†
			Ankle	0.79	1.64†	0.19*	0.49
		Min	Hip	0.72	1.52†	0.24*	0.28*
			Knee	2.84†	3.69†	2.33†	2.66†
			Ankle	1.94†	2.15†	1.79†	1.39†
		ROM	Hip	--	--	1.59†	1.41†
			Knee	--	--	0.84†	1.01†
			Ankle	--	--	2.03†	3.25†

* Effect size ≈ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 17 Effect size (r) comparing joint angles of the Warrior II to those to ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Warrior II	Sagittal	Max	Hip	4.88†	8.73†	5.26†	7.70†
			Knee	0.88†	0.33*	1.99†	1.89†
			Ankle	0.78	0.15*	0.26*	4.00†
		Min	Hip	2.21†	3.10†	2.13†	1.89†
			Knee	2.21†	2.29†	2.00†	2.19†
			Ankle	3.08†	2.76†	2.16†	2.72†
		ROM	Hip	--	--	0.86†	2.70†
			Knee	--	--	4.57†	5.33†
			Ankle	--	--	2.84†	7.20†
	Frontal	Max	Hip	2.31†	5.12†	2.26†	2.33†
			Knee	4.46†	5.98†	2.41†	2.58†
			Ankle	0.33*	1.13†	0.52	0.26*
		Min	Hip	9.52†	9.52†	9.96†	9.51†
			Knee	3.62†	4.44†	3.12†	3.49†
			Ankle	2.00†	2.22†	1.88†	1.50†
		ROM	Hip	--	--	5.99†	6.08†
			Knee	--	--	0.19*	0.43
			Ankle	--	--	1.65†	2.94†

* Effect size ≈ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 18 Effect size (r) comparing joint angles of the Triangle to those to ADL average and individual ADL movements

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Triangle	Sagittal	Max	Hip	5.07†	9.38†	5.65†	8.18†
			Knee	1.19†	0.17*	2.20†	2.11†
			Ankle	1.44†	0.21*	0.50	3.22†
		Min	Hip	1.60†	2.48†	1.47†	1.23†
			Knee	3.37†	3.04†	3.04†	2.93†
			Ankle	2.37†	1.72†	2.70†	1.54†
		ROM	Hip	--	--	--	3.69†
			Knee	--	--	--	1.47†
			Ankle	--	--	--	1.70†
	Frontal	Max	Hip	2.39†	5.51†	2.40†	2.52†
			Knee	3.31†	4.20†	2.02†	2.23†
			Ankle	0.13*	0.96†	0.70	0.15*
		Min	Hip	10.79†	10.65†	11.41†	10.86†
			Knee	0.29*	1.44†	0.41	0.21*
			Ankle	1.83†	2.07†	1.71†	1.29†
		ROM	Hip	--	--	7.72†	7.81†
			Knee	--	--	2.37†	2.43†
			Ankle	--	--	1.18†	2.55†

* Effect size ≈ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

4.2 Kinetic

4.2.1 Maximal Ground Reaction Force and Linear Impulse

The largest GRF (% of body weight) of the right foot (Figure 12) is in the first half of the movement for all three yoga postures. Once the right foot is loaded the GRF remains between 50-70% of the body weight. Through Figure 12 and Figure 13, we see that most of the bodyweight is distributed into the leading right foot (70% of bodyweight) compared to the left foot (30% of bodyweight) for all 3 yoga movements.

The largest linear impulse (Figure 14) in the right limb is found at the Lunge. The least loaded for the right limb in the Warrior II and slightly more for the Triangle pose.

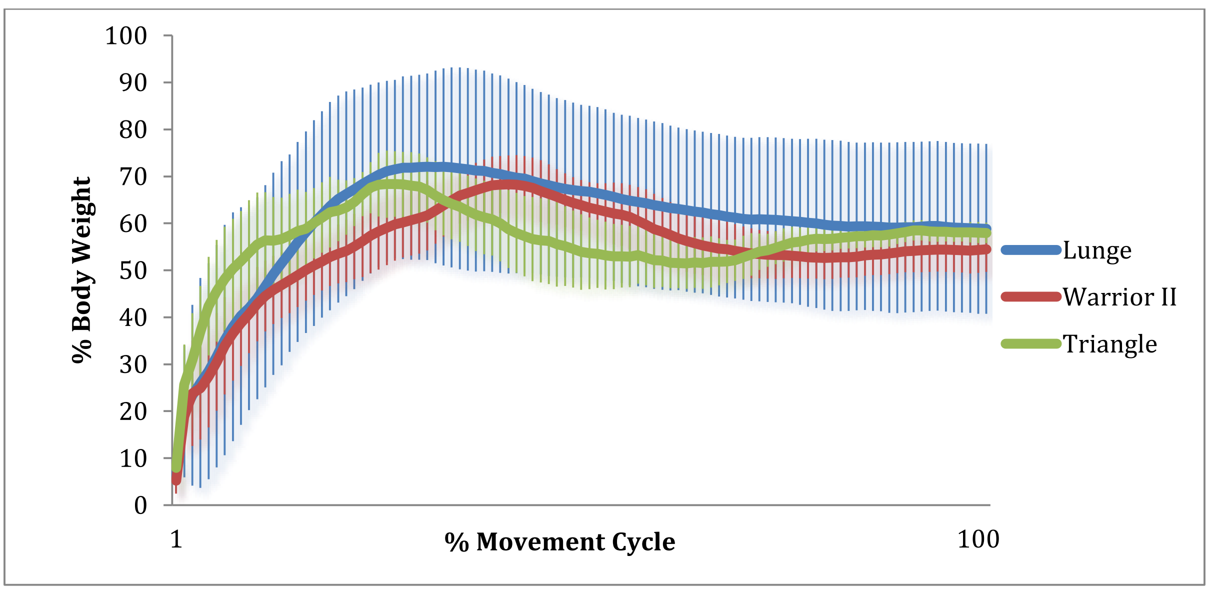

Figure 12 Normalized ground reaction force (%BW) of the right leg in a movement cycle of 3 yoga movements respectively.

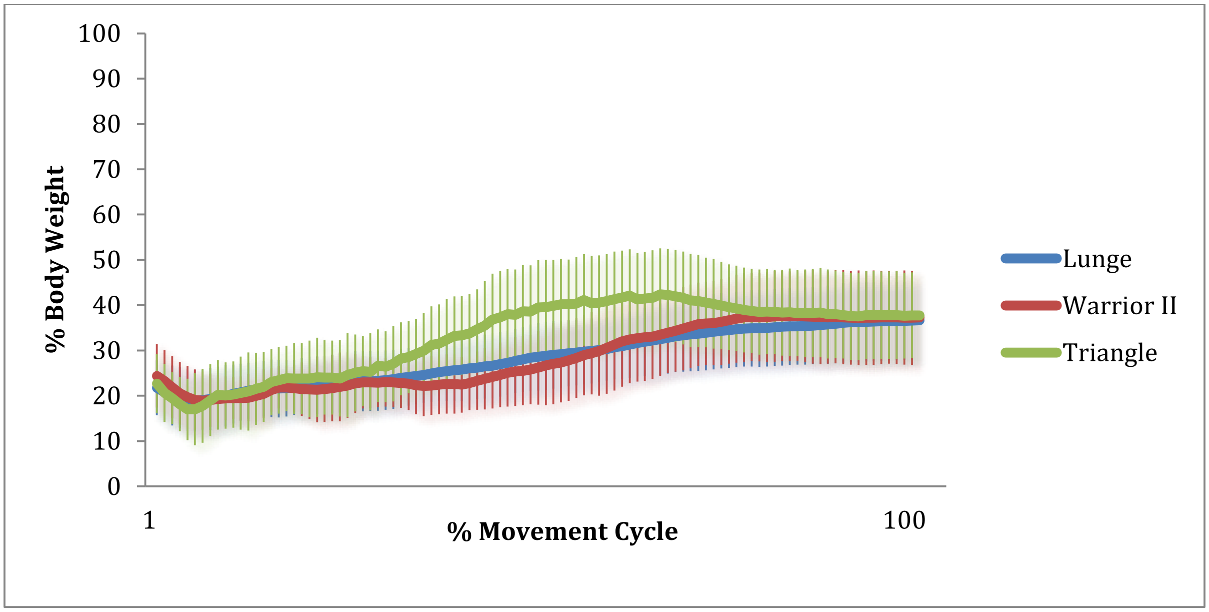

Figure 13 Normalized ground reaction force (%BW) of the left leg throughout the 3 yoga movements.

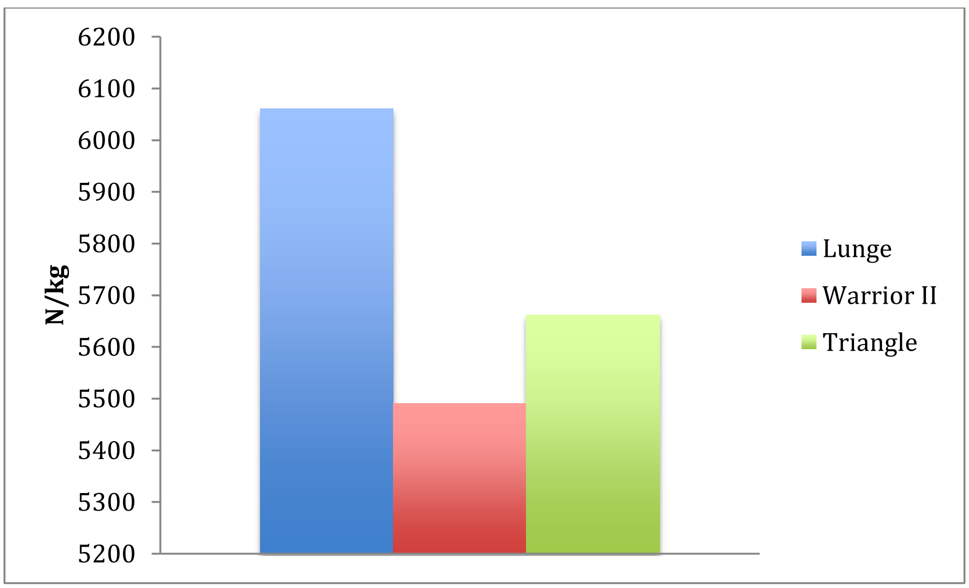

Figure 14 Total linear impulse of the right leg (N/kg) during individual yoga movement cycle.

4.2.2 Peak Joint Moments and Angular Impulse

Figure 15 and 16 present the joint moments patterns of the hip, knee and ankle in three yoga movements. The curves were plotted according to the average values of the joint moment in one movement cycle. The table 19 and 20 show the average peak joint moment of the hip, knee and ankle generated during the movements in both the sagittal and frontal plane for all of the yoga movements and the ADL as well as the average for each individual yoga and ADL activity.

Sagittal

Hip joint

All three yoga postures exhibited hip flexor moment without any extensor moments were throughout the entire movement cycle. The hip flexor moment patterns are distinct for each of the yoga postures (Figure 15). The largest hip flexor moment is present in the Lunge (1.90 Nm/kg) with the Warrior II (1.45 Nm/kg) and Triangle (1.38 Nm/kg) reaching a similar peak value (Table 19). The hip flexor moments relate to only hip flexion angles (Figure 10a).

The peak yoga hip flexor moments (1.58 Nm/kg) differed to those of ADL (0.47Nm/kg) by 235.03% (Table 19-21). There was no extensor moment generated during yoga movement. Therefore the extensor moments during ADL (0.41 Nm/kg) were greater by 119.07%. All differences were notable (>10%) when comparing yoga average and individual movements of hip extensor and flexor moments to those of ADL and individual ADL movements (Tables 19-24).

Knee joint

The peak knee flexor moments were 0.31 Nm/kg in the Lunge, 0.25 Nm/kg in the Warrior II, and the largest flexor moment, 0.94 Nm/kg in the Triangle (Table 19). Interestingly, while the extensor moments are present in all yoga movement, only the knee of subjects practicing Triangle pose move into knee extension angles, with 9.52° of extension (figure 10b).

Some knee joint moments data were not available during ADL due to the data source reporting only specific values, but the percentage of change was notable (>10%) for all available data except when comparing the knee extensor moment during Triangle pose to those during walking (5.56%) and stair ascent (0.91%) (Table 24).

Ankle joint

The joint moments for all three poses are erratic and the Figure 15c demonstrates jagged joint moments with visible sizeable standard deviation. There is no plantarflexor moment generated in any of the yoga movements, however, figure 10c clearly demonstrates the ankle in plantarflexion in Triangle pose for the last 75% of the movement cycle. The peak dorsiflexion moments are 0.80Nm/kg for the Lunge, 0.61 Nm/kg for the Warrior II and for Triangle (Table 19).

Since the ankle plantarflexor moments are absent for stair ascent and descent, the only plantarflexor comparison available was yoga movements to walking, all differences were notable (Table 21-24). Though the dorsiflexor moments were all notably different and larger in ADL compared to yoga movements (Table 19-24), none of these could be considered meaningful based on effect size (Table 25-28).

Frontal

Hip joint

The hip joint moments in the frontal plane indicate that hip adductors were active for all three postures (Figure 16a). The most adduction moment is present in Triangle (0.850 Nm/kg). Thought the peak value for hip adduction moment in the Lunge (0.695 Nm/kg) is slightly bigger than Warrior II (0.615 Nm/kg) (Table 19), upon closer inspection of the joint moment pattern, we notice that at 50% of the movement cycle, the joint adduction moment dips and then approaches neutral in the Lunge rather than progressively increasing in adduction moment as is apparent with the Warrior II and Triangle pose.

All available data was compared and the percentage of change was notable when comparing yoga movements to ADL movements. The differences are most notable when comparing Warrior II minimal hip adduction moments to stair descent (652.92%) and when comparing Triangle minimal adduction hip moments to stair descent (939.82%) where the yoga poses exhibited more hip abductor moments than stair descent (Table 21-24). The effect sizes are all well above the significance cutoff therefore the hip adduction is notably greater in yoga movement over average and individual ADL (Table 25-28).

Knee joint

The knee in triangle is travels into slight adduction of 1.94° (Table 9) while expressing the largest of knee joint adduction moments (varum) (0.30 Nm/kg) compared to Lunge (0.06 Nm/kg) and Warrior II (0.07 Nm/kg) (Table 19). It should be noted that these minimal values are upon initiation of the movement cycle. Triangle pose is the only posture to generate remarkable knee adduction moment after the initiation of the movement, at approximately 40% of the movement cycle (Figure 16b).

The knee abduction moments are the most notably different when comparing abduction in yoga averages and individual yoga posture joint moments to ADL averages (500-700%) and individual joint moments, however all differences, in knee abduction as well as adduction were deemed notable (>10%) (Table 21-24). The effect size confirmed that these differences were notable (Table 25-28) except when considering knee adduction when practicing Triangle versus stair walking (Table 28).

Ankle joint

The joint moments for all three poses are erratic and the Figure 16c demonstrates jagged joint moments with visibly sizeable standard deviation. The ankle joint moments are predominately negative values, ankle adductor moments (eversion joint moment) with the peak value being 0.06 Nm/kg for Warrior II and 0.07 Nm/kg for Lunge and Triangle pose (Table 19).

Yoga movements were notably changed compared to ADL in all ankle joint moments (Table 20-24). The most notable change is when comparing stair ascent ankle joint adduction moment to the greater ankle adduction joint moments of the Lunge (769.89%), to the Warrior II (711.96%), and to the Triangle (788.63%). The effect size confirms that these large differences in ankle adduction are notably different (Table 25-28). The joint moments were not notably different when compared to walking.

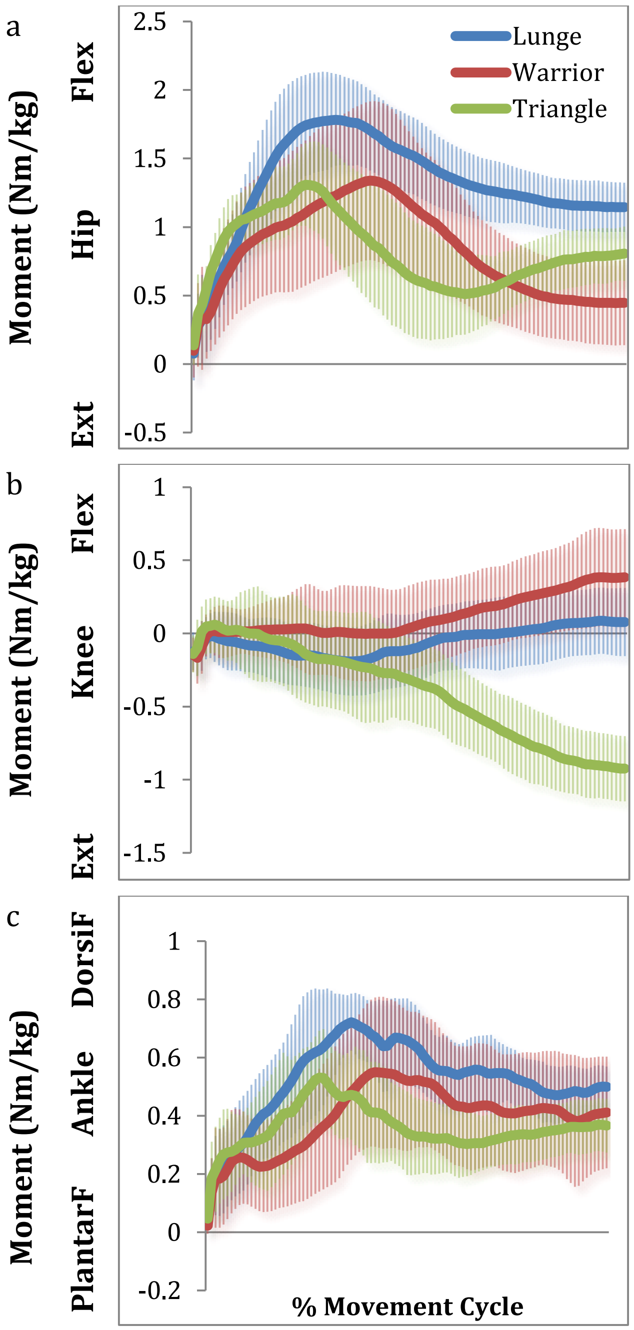

Figure 15 Mean and standard deviation of joint moments (Nm/kg) during lunge (blue), Warrior II (red), and Triangle (green) in the sagittal plane (a) hip flexion and extension (b) knee aflexion and extension (c) ankle plantar flexion and dorsi flexion.

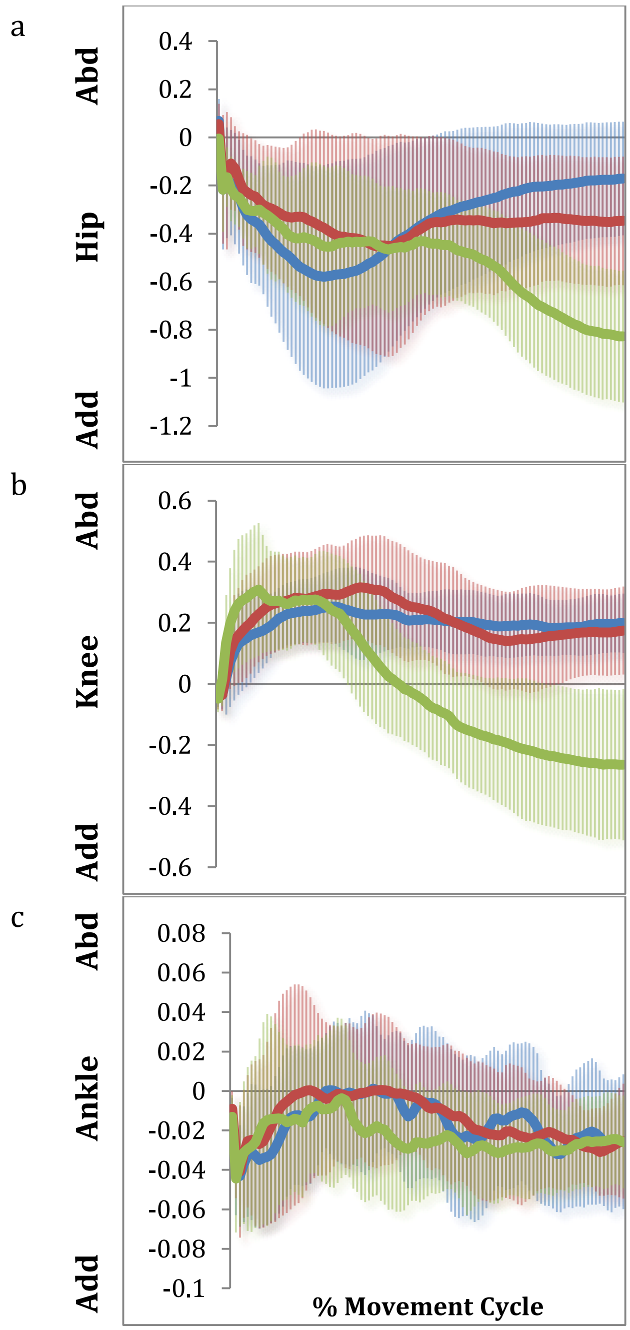

Figure 16 Mean and standard deviation of joint moments (Nm/kg) during lunge (blue), Warrior II (red), and Triangle (green) in the frontal plane a) hip adduction and abduction (b) knee valgus and varus (c) ankle adduction and abduction.

Table 19 Bodyweight normalized peak joint moments (Nm/kg) in the sagittal and frontal plane during one cycle of individual and combined average of yoga movements (Lunge [n=13], Warrior II [n=12], and Triangle [n=12s]).

Activity	Movement	Direction	Hip	SD	Knee	SD	Ankle	SD
Yoga Averages	Flex/Ext	Max	1.58	0.28	0.24	0.14	0.67	0.11
		Min	0.08	0.02	-0.50	0.38	0.03	0.01
	Abs/Add	Max	0.07	0.03	0.37	0.04	0.03	0.00
		Min	-0.72	0.12	-0.14	0.13	-0.07	0.00
Lunge	Flex/Ext	Max	1.90	0.34	0.16	0.20	0.80	0.11
		Min	0.07	0.20	-0.31	0.15	0.04	0.04
	Abs/Add	Max	0.08	0.09	0.33	0.10	0.03	0.32
		Min	-0.69	0.46	-0.06	0.04	-0.07	0.02
Warrior II	Flex/Ext	Max	1.45	0.56	0.40	0.34	0.61	0.25
		Min	0.06	0.19	-0.25	0.12	0.02	0.03
	Abs/Add	Max	0.09	0.11	0.37	0.17	0.03	0.04
		Min	-0.62	0.41	-0.07	0.06	-0.06	0.03
Triangle	Flex/Ext	Max	1.38	0.38	0.16	0.27	0.61	0.15
		Min	0.10	0.10	-0.94	0.22	0.04	0.04
	Abs/Add	Max	0.03	0.12	0.40	0.21	0.02	0.03
		Min	-0.85	0.26	-0.30	0.22	-0.07	0.03

Note: Positive values indicate flexion and abduction and negative values indicates extension and adduction.

Table 20 Mean and standard deviation for bodyweight normalized peak joint moments (Nm/kg) in the sagittal and frontal plane movements during one cycle of individual and combined average of ADL movements (walking [n=12], stair Ascent [n=19], and stair descent [n=19]).

Activity	Movement	Direction	Hip	SD	Knee	SD	Ankle	SD
ADL Averages	Flex/Ext	Max	0.47	0.36	--	--	--	--
		Min	-0.41	0.34	-0.84	0.13	-1.24	0.22
	Abd/Add	Max	--	--	-0.07	0.16	-0.02	0.10
		Min	-0.53	0.49	-0.49	0.09	-0.11	0.11
Walking	Flex/Ext	Max	0.89	0.89	0.21	0.66	0.24	1.97
		Min	-0.47	0.15	-0.89	0.64	-1.47	0.97
	Abd/Add	Max	0.30	0.34	0.12	0.74	0.05	0.11
		Min	-1.06	1.55	-0.59	1.42	-0.21	0.95
Ascending Stairs	Flex/Ext	Max	0.26	0.18	--	--	--	--
		Min	-0.72	0.17	-0.94	0.29	-1.20	0.23
	Abd/Add	Max	-0.31	0.14	-0.15	0.11	-0.14	0.10
		Min	-0.44	0.18	-0.44	0.19	0.01	0.02
Descending Stairs	Flex/Ext	Max	0.26	0.12	--	--	--	--
		Min	-0.04	0.32	-0.70	0.29	-1.03	0.13
	Abd/Add	Max	--	--	-0.17	0.17	0.02	0.02
		Min	-0.08	0.24	-0.44	0.25	-0.12	0.08

* Table adapted from work previously done in our laboratory (N. H. Law, 2013; Lee, 2011)
Note: Positive values indicate flexion and abduction and negative values indicates extension and adduction.

Table 21 Percentage of change (%) comparing joint moments Yoga averages and ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Yoga Averages	Flex/Ext	Max	Hip	235.03	77.78	505.59	495.88
			Knee	--	14.63	--	--
			Ankle	--	178.75	--	--
		Min	Hip	119.07	116.56	110.90	292.49
			Knee	41.16	44.04	47.47	28.98
			Ankle	102.76	102.32	102.84	103.31
	Abd/Add	Max	Hip	--	77.15	121.62	--
			Knee	658.43	200.25	348.19	313.97
			Ankle	216.57	41.33	120.54	69.22
		Min	Hip	114.09	107.00	116.90	190.70
			Knee	37.40	47.91	29.73	31.02
			Ankle	136.82	118.95	289.23	131.98

* Percentage of change < 10% - Not notable change

† Percentage of change > 1000% - Very notable changes

Table 22 Percentage of change (%) comparing joint moments of lunge averages and ADL average and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Lunge	Flex/Ext	Max	Hip	304.07	114.41	630.40	618.69
			Knee	--	22.48	--	--
			Ankle	--	231.01	--	--
		Min	Hip	118.12	115.73	110.36	282.90
			Knee	63.71	65.49	67.60	56.20
			Ankle	103.16	102.65	103.25	103.79
	Abd/Add	Max	Hip	--	72.92	125.63	--
			Knee	598.37	167.96	321.50	290.96
			Ankle	231.02	34.07	123.08	90.19
		Min	Hip	32.02	34.35	58.34	750.03
			Knee	88.38	90.33	86.95	87.19
			Ankle	36.62	67.38	769.89	44.96

* Percentage of change < 10% - Not notable change

† Percentage of change > 1000% - Very notable changes

Table 23 Percentage of change (%) comparing joint moments of warrior II averages and ADL average and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Warrior II	Flex/Ext	Max	Hip	207.82	63.34	456.42	447.50
			Knee	--	89.50	--	--
			Ankle	--	153.96	--	--
		Min	Hip	113.81	112.00	107.90	239.44
			Knee	70.77	72.20	73.90	64.72
			Ankle	101.68	101.41	101.72	102.01
	Abd/Add	Max	Hip	--	69.68	128.70	--
			Knee	666.87	204.79	351.94	317.20
			Ankle	218.69	40.27	120.91	72.29
		Min	Hip	16.93	41.85	40.25	652.92
			Knee	85.96	88.32	84.24	84.53
			Ankle	42.10	70.20	711.96	49.72

* Percentage of change < 10% - Not notable change

† Percentage of change > 1000% - Very notable changes

Table 24 Percentage of change (%) comparing joint moments of triangle averages and ADL average and individual ADL movements.

Activity	Movement	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Triangle	Flex/Ext	Max	Hip	193.18	55.57	429.95	421.45
			Knee	--	23.13	--	--
			Ankle	--	151.29	--	--
		Min	Hip	125.28	121.95	114.45	355.13
			Knee	10.99	5.56*	0.91*	33.98
			Ankle	103.45	102.89	103.54	104.13
	Abd/Add	Max	Hip	--	88.85	110.55	--
			Knee	710.04	228.00	371.13	333.74
			Ankle	200.01	49.67	117.62	45.18
		Min	Hip	61.49	19.69	93.69	939.82
			Knee	39.56	49.71	32.15	33.40
			Ankle	34.85	66.47	788.63	43.42

* Percentage of change < 10% - Not notable change

† Percentage of change > 1000% - Very notable change

Table 25 Effect size (r) comparing joint moments of yoga averages to those to ADL average and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Yoga Averages	Sagittal	Max	Hip	3.41†	1.04†	5.51†	6.00†
			Knee	1.51†	0.07*	--	--
			Ankle	--	0.31*	--	--
		Min	Hip	2.01†	0.95†	6.68†	0.52
			Knee	1.22†	0.74	1.32†	0.12*
			Ankle	8.06†	2.05†	7.66†	11.34†
	Frontal	Max	Hip	--	0.95†	3.86†	--
			Knee	3.66†	0.47	--	4.49†
			Ankle	0.75	0.26*	2.46†	0.71
		Min	Hip	0.54	0.31	1.84†	3.38†
			Knee	3.09†	0.95†	1.79†	1.51†
			Ankle	0.52	0.21*	5.55†	1.03†

* Effect size ≈ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 26 Effect size (r) comparing joint moments of the Lunge to those to ADL average and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Lunge	Sagittal	Max	Hip	4.09†	1.51†	6.01†	6.40†
			Knee	--	0.10*	--	--
			Ankle	--	0.40	--	--
		Min	Hip	1.74†	3.13†	4.35†	0.43
			Knee	3.79†	1.25†	2.72†	1.68†
			Ankle	7.95†	2.20†	7.57†	10.89†
	Frontal	Max	Hip	--	0.87†	3.37†	--
			Knee	2.87†	0.39	4.48†	3.61†
			Ankle	0.24*	0.07*	0.73	0.07*
		Min	Hip	0.35	0.32*	0.73	1.66†
			Knee	6.50†	0.53	2.74†	2.15†
			Ankle	0.60	0.21*	4.01†	0.98†

* Effect size ≈ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 27 Effect size (r) comparing joint moments of the Warrior II to those to ADL average and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Warrior II	Sagittal	Max	Hip	2.07†	0.75	2.83†	2.90†
			Knee	--	0.36	--	--
			Ankle	--	0.26*	--	--
		Min	Hip	1.69†	3.12†	4.37†	0.37
			Knee	4.74†	1.39†	3.10†	2.02†
			Ankle	7.91†	2.18†	7.52†	10.95†
	Frontal	Max	Hip	--	0.82†	3.26†	--
			Knee	2.66†	0.47	3.70†	3.27†
			Ankle	0.71	0.24*	2.30†	0.39
		Min	Hip	0.20*	0.39	0.55	1.58†
			Knee	5.66†	0.52	2.59†	2.05†
			Ankle	0.56	0.22*	2.88†	1.04†

* Effect size $\approx$ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 28 Effect size (r) comparing joint moments of the Triangle to those to ADL average and individual ADL movements.

Activity	Plane	Direction	Joint	ADL Averages	Walk	Ascending Stairs	Descending Stairs
Triangle	Sagittal	Max	Hip	2.46†	0.72†	3.77†	3.96†
			Knee	--	0.10*	--	--
			Ankle	--	0.26*	--	--
		Min	Hip	2.03†	4.47†	5.92†	0.61
			Knee	0.51	0.10*	0.03*	0.91†
			Ankle	8.01†	2.21†	7.62†	11.06†
	Frontal	Max	Hip	--	1.03†	2.66†	--
			Knee	2.51†	0.52	3.33†	3.06†
			Ankle	0.66	0.30*	2.31†	0.30*
		Min	Hip	0.82†	0.19*	1.86†	3.10†
			Knee	1.15†	0.29*	0.68	0.63
			Ankle	0.47	0.20*	3.39†	0.92†

* Effect size $\approx$ 0.2 - No notable effect

† Effect size > 0.8 - Notable effect

Table 29 Total, positive and negative of the angular impulses (Nm) for the average yoga movement as well as individual yoga movement in the sagittal and frontal plane of the hip, knee and ankle.

Activity	Movement	Hip Total	Hip (+)	Hip (-)	Knee Total	Knee (+)	Knee (-)	Ankle Total	Ankle (+)	Ankle (-)
Yoga Averages	Flex/Ext	99.54	99.54	0.00	20.74	4.72	-16.02	42.86	42.86	0.00
	Abd/Add	40.21	0.04	-40.17	20.18	16.78	-3.40	1.82	0.00	-1.82
Lunge	Flex/Ext	132.35	132.35	0.00	8.51	1.56	-6.95	52.78	52.78	0.00
	Abd/Add	34.41	0.07	-34.34	20.01	19.93	-0.08	1.66	0.00	-1.66
Warrior II	Flex/Ext	83.64	83.64	0.00	12.69	12.26	-0.43	39.53	39.53	0.00
	Abd/Add	34.83	0.05	-34.78	21.42	21.35	-0.08	1.46	0.00	-1.46
Triangle	Flex/Ext	82.61	82.61	0.00	41.02	0.34	-40.69	36.26	36.26	0.00
	Abd/Add	51.40	0.00	-51.40	19.12	9.06	-10.06	2.33	0.00	-2.33

Note: Positive values indicate flexion and abduction and negative values indicates extension and adduction.

Upon visual inspection of distribution of the angular impulse, we can determine that the hip contributed the most in the total angular impulse in the lower limb (combined angular impulse of the hip, knee, and ankle) distribution of both the sagittal and frontal plane (Figure 17 and 18), ranging from 52-71% of the total angular impulse of the lower limb for all 3 studied yoga postures.

It is interesting to notice the distribution of the angular impulse in the sagittal plane. In all 3 yoga postures in the sagittal plane, the ankle contributes about a quarter of the total angular impulse. In the Lunge (Figure 17a) the knee contributes 5% versus 68% for the hip, in the Warrior II (Figure 18b) the knee contributes 9% versus 62% for the hip, and in the Triangle (Figure 18c) the knee contributes 25% versus 52% for the hip. The ankle remains similar in its total contribution while knee and hip share the load differently in each individual posture.

In the frontal plane, the ankle contributes to 3% of the angular impulse while the greatest contribution is found in the hip for all three postures (Figure 18). The largest knee angular impulse contribution can be found in the Warrior II at 37% (Figure 18b) and the Lunge at 36% (Figure 18a). Again, the ankle remains similar in its total contribution while knee and hip share the load differently in each individual posture.

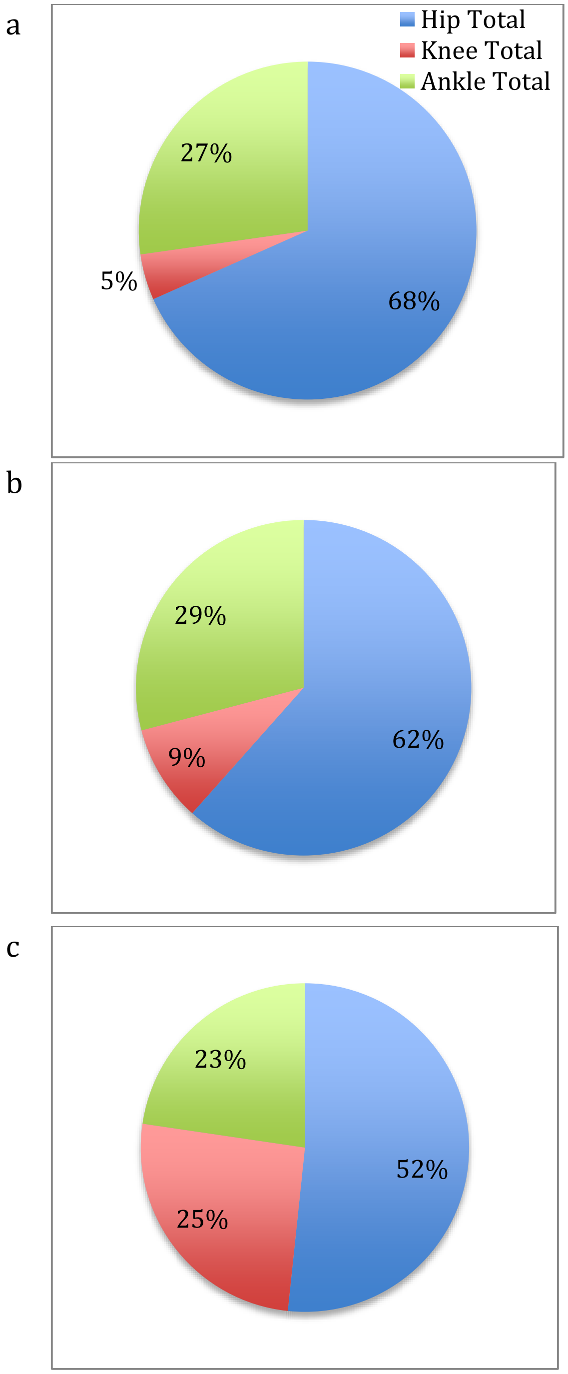

Figure 17 Contribution of the angular impulse (%) from the hip (blue), knee (red), and ankle (green) of the (a) lunge (b) Warrior II (c) Triangle in the total angular impulse of the lower limb in the sagittal plane.

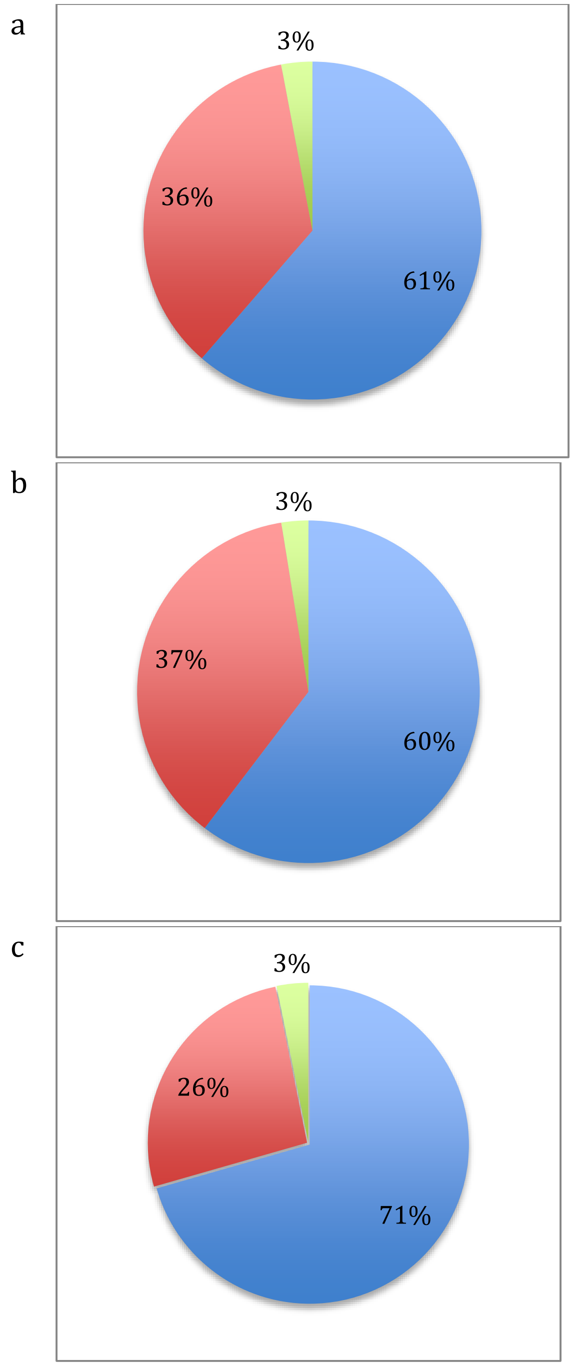

Figure 18 Contribution of the angular impulse (%) from the hip (blue), knee (red), and ankle (green) of the (a) lunge (b) Warrior II (c) Triangle in the total angular impulse of the lower limb in the frontal plane.

5 Discussion and Conclusion

The purpose of this study was to establish a motion pattern for three fundamental yoga movements by characterizing the kinetics and kinematics associated with the hip, knee, and ankle joints in a population of healthy yoga teachers. These motion patterns were then compared to the motion patterns of ADL in a sex-matched group (N. H. Law, 2013; Lee, 2011). This is first time motion patterns have been quantitatively developed for three fundamental yoga postures and their unique kinetics and kinematics characterized. The motion patterns of the Lunge and the Warrior II poses follow similar joint angle, joint moment, and angular impulse patterns, whereas the Triangle pose creates distinctly different patterns in most joints and planes. Triangle pose expressed the largest ROM in each joint for both the sagittal and the frontal plane. This suggests that similar yoga poses should be categorized and sorted by biomechanical effect, and that these groups may have similar demanding to motor system and subsequently might result in similar impact on the system, in terms risk and benefit profiles. The motion patterns created in this study will help inform yoga teachers and practitioners of the possible benefits and risks involved when practicing these three fundamental poses by using scientifically based evidence.

The hip contributed a large angular impulse in the lower limb in all three yoga movements compared to the knee and ankle, suggesting that yoga may have strong training effect to hip and may be a beneficial at improving hip strength and ROM. The finding is particularly interesting for those population, such as elderly people who utilize the hip strategy during gait (Kean, Bennell, Wrigley, & Hinman, 2015). On average, yoga expressed greater total hip ROM and hip flexor moments when compared to ADL, supporting that yoga should be studied further as a potential training modality to improve gait

(DiBenedetto et al., 2005; Kean et al., 2015). The knee abduction angle and abductor moments were greater in yoga than ADL. Thus, this point should be kept in mind when consider yoga as a therapeutic or rehabilitation approach for knee joint disorders. Knee adduction angle is known to cause reduction in patella cartilage volume in valgus knees in OA patients (Teichtahl, Wluka, & Cicuttini, 2008). Those who suffer from medial compartment knee OA should be cautioned from pursuing certain yoga poses (Miyazaki et al., 2002). No increase in joint angles or moments was apparent for the ankle joint, suggesting that the studied yoga postures do not improve dynamic stability in the healthy participants who utilize ankle strategies for balance (R. H. Whipple, L. I. Wolfson, & P. M. Amerman, 1987).

5.1 Yoga Motion Pattern

The theoretical understanding of movement plays an important role in biomechanical studies. Descriptive studies are the first step in a new topic (Winter, 2004), and upon which future research may base their interventions and recommendations. Motion patterns of gait have been used extensively in applied research and clinical application, and the motion patterns of yoga movements will have an equivalent potential to serve as a foundation for future applied research and clinical applications such as; developing appropriate yoga rehabilitation program for the people with chronic disease, OA, stroke, comparison to other training programs for efficacy and safety as well as implementation of yoga therapy programs in the clinical setting when dealing with rehabilitation. Similarities were observed between the Lunge and Warrior II poses when examining the yoga movement patter in terms of the joint angle pattern (Figure 10 and 11), the joint moment pattern (Figure 15 and 16), as well as the angular impulse (Figure 17 and

18). In both Lunge and Warrior II, little ROM was observed in the knee and ankle joint angles, and joint moment was found to be fairly consistent. It is interesting to note that in the Lunge and Warrior II poses, the knee joint reaches a maximal flexion angle of 73.76° and 67.69° respectively. These poses are typically described in yoga training manuals as having a 90° bend, and therefore the present study found these values to be 18% to 32% less than what is classically instructed in a yoga class. This suggests that even experts do not perform the movement as it is ideally described and instructed.

Triangle pose was found to be distinct from the other chosen postures as it expressed the largest ROM for all three joints in both the sagittal and frontal plane and it was shown to exhibit meaningful percentage of change in knee abduction angles and moments, ankle plantarflexion angles, and greater sagittal ankle impulse. Though the knee's contribution to the angular impulse in the frontal plane is much less for Triangle pose compared to the other two postures, the adduction moment might be more meaningful because the knee was also found to be in slight extension, beyond the baseline measurement. This suggests that Triangle pose, and other similar poses, should be practiced with caution, as previous studies have suggested that larger adduction moments combined with knee hyperextension causes unnecessary strain on the knee joint. Practicing Triangle pose caused the knee to extend over its baseline by 9.5° on average. As 6.3±3.8° over baseline extension has been shown to be significantly correlated to anterior cruciate ligament (ACL) impingement in uninjured knees (Jagodzinski, Richter, & Pässler, 2000), strain on the oblique popliteal ligament that has shown to be the primary ligamentous restraint in knee hyperextension (Morgan, LaPrade, Wentorf, Cook, & Bianco, 2010), as well as undue strain on the posterior cruciate ligament (PCL) which is particularly vulnerable in knee hyperextension (Davies, Wallace, & Malone, 1980). Therefore, it is important to caution even yoga experts to bend their knees slightly in Triangle pose so as to avoid hyperextension and the associated knee injuries. Knee injuries, as stated earlier, were the reported case studies of yoga injury (Bianchi et al., 2004; Patel & Parker, 2008).

Practicing Triangle pose may also bring a concern to vulnerable populations, such as those who suffer from knee OA. It has been suggested by previous studies that the knee adduction moment is an important biomechanical parameter in predicting pain and increased risk in the medial compartment of the knee (Kean et al., 2015), and that the risk of progression of knee OA increased 6.46 times with a 1% increase in adduction moment (Miyazaki et al., 2002). To protect against further degeneration of the joint capsule, it has been suggested that those who suffer from knee OA increase hip abductor moment (Chang et al., 2005), as individuals with knee OA have significantly reduced isometric and isokinetic hip abductor strength (Kean et al., 2015). Since no hip abductor moments are present in any of the yoga poses examined in the present study, and lower knee abductor moments links reduced knee pain, it would be interesting future to examine poses with hip abductor moments or explore various instructional wording to encourage hip abductor strength in Triangle pose in order to reduce knee adduction moment and protect those with knee OA.

Reduced abductor and adductor strength was found to be prevalent in elderly people (Johnson, Mille, Martinez, Crombie, & Rogers, 2004) and this reduced strength is associated with higher risks of falls (Hilliard et al., 2008; S. R. Lord, Rogers, Howland, & Fitzpatrick, 1999; Maki, Edmondstone, & McIlroy, 2000), the greater hip adduction moments present in the yoga movements may suggest that the practice of yoga can be considered for future studies regarding training mechanisms that reduce falls, thereby improving dynamic stability. This may also be useful practice for those who suffer from varus knee deformities as they benefit from strengthening hip adductor muscles (Yamada, Koshino, Sakai, & Saito, 2001).

Overall, yoga solicits the hip joint moment in the frontal plane, which is associated with knee health and dynamic stability. Future studies should examine how to solicit more abduction moment in order to contribute to overall knee health.

In all three yoga poses, the GRF for the leading right leg never exceeded 80% of the body weight. As such, yoga gait, similarly to Tai Chi gait, results in lower GRF compared with walking (Mao, Li, & Hong, 2006; Wu & Hitt, 2005; Wu & Millon, 2008) which is likely due to the slow movement speed of yoga with a slow and silent foot strike, much like Tai Chi (N. Y. Law & Li, 2014). Future analysis should examine the kinetics and kinematics of the support left leg to determine if yoga may be a suitable excersise, like Tai Chi, for elderly people because higher GRF results in higher loading of the lower limb joints and is associated with joint pain in people with knee joint disorders (Radin, Yang, Riegger, Kish, & O'Connor, 1991).

The hip contributed 50-70% of the angular impulse of the lower limb in all three yoga movements, suggesting that the high hip loading in yoga may be a beneficial for those who rely on hip strategies for dynamic stability in gait. Hip strategies, rather than ankle strategies, are common in the elderly and characterized by larger perturbation to the body movement, especially by the sway in the hips (Runge, Shupert, Horak, & Zajac, 1999). The practice of yoga should therefore be recommended to the elderly, who typically use hip strategies, rather than ankle strategies, to maintain postural stability (Horak, 2006), to those with the FoF (Horak, 2006), and to those with diabetes and peripheral neuropathy who suffer from impaired sensation in ankles and feet (M. J. Mueller, Minor, Sahrmann, Schaaf, & Strube, 1994). The ankle contribution in the sagittal plane represented about 25% of the contribution of the angular impulse (Figure 17). Ankle dorsiflexion and plantarflexion strength is negatively correlated with a history of falls in the elderly (R. Whipple, L. Wolfson, & P. Amerman, 1987). This further suggests that the elderly should consider the practice of yoga to improve postural stability for its contribution in hip and ankle strengthening potential in the elderly; however, as it will be demonstrated later, it may not be sufficient in healthy individuals.

5.2 Yoga and ADL Comparison

5.2.1 Step Length

The average step length in a yoga practice is 1.63m, which is longer than the 0.74m step length measured for the activity of walking in healthy participants (Lee, 2011). Studies have reported that the hip ROM may improve gait functions (DiBenedetto et al., 2005) and that longer step lengths may provide training towards improved gait in the elderly (Judge, Davis, & Ounpuu, 1996). This suggests that practicing yoga may serve as a way to increase stride length thereby preventing deterioration of gait functions by maintaining a normal step length.

5.2.2 Joint Angles and Joint Moments

The ROM was notable, based on the percentage of change, greater in the sagittal and frontal hip movement as well as the frontal knee movement for yoga averages compared to ADL. On average, yoga has more total hip ROM and hip flexor moments when compared to

ADL similar to studies that suggested that yoga is a training modality to improve gait (DiBenedetto et al., 2005; Kean et al., 2015). The absence of hip extensor moments was expected as only stepping forward with the right limb was studied. Therefore we cannot compare the hip joint moments of the hip in bow (-1.4 Nm/kg) and running (-1.6 Nm/kg) from a previously conducted study (Omkar et al., 2011). Future studies should include data processing both the right and left sides to allow for more comparisons.

The knee abduction angle and abductor moment was notably greater, and the knee adduction angle and adductor moments notably smaller in the Lunge and Warrior II poses compared to ADL. Based on these results, these poses may serve as a safe training effect for frontal knee movement. It may be hypothesized that knee injuries may occur more readily in typical ADL compared to yoga movements. However, caution is recommended to those suffering from knee disorders such as OA (Kean et al., 2015; Miyazaki et al., 2002).

The largest knee joint moment in this study was found to be -0.94Nm/kg for the knee extensor in Triangle pose. This is smaller than the peak joint moment reported in a previous yoga study (Omkar et al., 2011). In this previous study, the knee moments of a yoga posture known as Eagle pose, reached -1.3 Nm/kg and was likened to a joint extensor moment of -1.40 Nm/kg found in running. Though no statistical comparison was made between Triangle knee extensor moments to those of Eagle pose or running, it is proposed that not all yoga postures will offer the same training opportunities. It should be noted that the previously mentioned knee extension moment found in Triangle pose was found to be larger than the other postures examined in this study, however, the knee extension moment is not different from walking (-0.89Nm/kg) and stair ascent (-0.94Nm/kg). This suggest that Triangle pose does not load the knee joint beyond typical ADL and can be practiced safely, provided that the participants adhere to the earlier suggestion of avoiding deep hyperextension.

Ankle joint muscles play an important role in postural stability (Hu & Woollacott, 1994) and ankle strategies are more commonly utilized in healthy populations (Horak, 2006). Research has found that weakness in the ankle in sagittal plane was linked with a history of falls in the elderly (R. Whipple et al., 1987). It is commonly suggested in yoga classes that the practice of yoga will improve balance. However, the study results suggest that there are no notable increase in the ankle joint angles and joint moments between the yoga postures studied and ADL. Therefore the impact of yoga practice on ankle joint muscles might be quite small. Although there were no notable differences between the ankle kinetic and kinematic values in averaged yoga and ADL movements. Interestingly, ankle angular impulse is considerable in the frontal plane suggesting that the ankle muscles contributing to medio-lateral movement are working hard during yoga which might be helpful in improving medio-lateral stability. However, closer examination of the ankle data demonstrates a notable difference in joint angles and joint moments in yoga movements compared to stair walking. As the joint angles and joint moments were higher in stair walking, it is likely that the chosen yoga postures would not adequately train an individual to complete the task of going up and down the stairs, as greater ankle joint moments correspond to improved stability (Stephen R. Lord, Ward, & Williams, 1996). Though it has been popularly suggested that physical activity and yoga could reduce the incidence of fall in the elderly (Schmid et al., 2010), the results from the present study suggest that the studied yoga postures are no more effective than regular ADL at improving dynamic stability in healthy participants when using ankle strategies but may contribute to improved postural stability for those who rely on hip strategies. Future studies should explore the ankle angles, joint moments as well as the center of pressure in various populations, especially those with FoF, to explore if other yoga poses may improve dynamic stability and ankle strategies in gait.

It is important to note that the ADL movements were compared to the yoga movements of healthy yoga experts. Thus, the aforementioned recommendations might not be suitable for untrained individuals whose yoga motion pattern may be different. Future studies should explore how novice practitioners compare to experts so as to generalize the advice given to yoga practitioners.

5.3 Study Limitations

Although great effort was made in participant recruitment and data collection, several study limitations were encountered.

Foremost, we were unable to recruit the anticipated number of participants. The population recruited for this study consisted of experienced, self-employed yoga teachers who tended to have limited time for non-compensated work hours. To improve participant involvement, future research might consider offering compensation for eligible yoga teachers.

The yoga experts performed the three yoga movements of this study as closely as possible to the normal conditions of regular practice. Participants were encouraged to move at their own pace and in a way that they felt was the ideal yoga movements. As such, participant variability increased. Another possible contributor to the variability of this study is the possible differences between yoga styles, which may lead to greater variable and alter the parametricity of the data. The yoga practitioners examined in this study enjoyed practicing an assortment of yoga styles, as evidenced by the practice frequency questionnaire (Appendix B). This variability could likely be minimized if the sample was pooled from a stricter or more regimented yoga school, where practitioners are encouraged to practice according to one style and often a set sequence (i.e. Ashtanga power yoga or Sivananda).

Another major limitation of this study is related to the marker visibility during motion capture. Various motion analysis studies have often reported errors associated in marker placement, usually due to adipose tissue artifact. None of the yoga studies discuss the difficulty of marker placement in slender and flexible yoga practitioners where markers can often, at least one trial per participant, become hidden in a deep flexible fold, most notably in the hip crease (along the RASIS and LASIS of the PiG marker set). The missing markers were reconstructed which may bias the data. The methodology of future yoga studies could be improved by collecting movements in one continuous trial starting from a position where all markers are visible (i.e. Mountain pose) as well as optimizing the marker placement, perhaps by using cluster marker sets. This would better mimic a true yoga practice and would help the researcher in minimizing missing markers. This approach would permit the calculation of the ROM throughout a full yoga practice as well as individual poses.

Finally, a major limitation of this study was the comparison to a population that was only sex-matched but not matched for age due to the limited availability of previously conducted research in our lab. Future studies should compare yoga movements to ADL of participants conducting both yoga and ADL movements.

5.4 Conclusion

The present study established motion patterns of three fundamental standing yoga postures, Lunge, Warrior II and Triangle, by examining the kinetics and kinematics of the lower limb in the healthy yoga experts while performing the three postures. In addition, we compared the measures from three yoga postures to floor walking and stair walking that are the activity of daily living (ADL), in order to know the biomechanical differences between yoga and ADL and provide scientific information for the application of yoga in improving ADL.

In summary, the results showed that the Lunge and Warrior II share similar motion patterns in terms of joint angles, joint moments, and angular impulse. The Triangle pose expressed the largest ROM of all yoga movements in all three joints in sagittal and frontal planes. The lunge expressed the largest total linear impulse. Triangle pose was the only yoga movement to express knee extensor and adductor moments. The hip contributed 50-70% of the angular impulse in the lower limb in all three yoga movements, indicating high demanding to hip muscle activity. When comparing to ADL, ROM was only greater in the sagittal and frontal motion of the hip and frontal motion of the knee, and most of the joint moments of the lower extremity were notably smaller in ADL for the minimal values and notably larger for the maximal values in yoga.

The findings suggest that the three yoga postures have higher demand to hip motion in the sagittal plane and knee motion in frontal plane. Yoga practitioner would do well to know the impact of the knee extended over the neutral position on musculoskeletal tissues when performing Triangle pose.. Yoga is of value to ADL movements because the joint angles and joint moments are similar or exceed those of ADL and therefore can serve as a compliment to maintain movement health and the ability to perform ADL.

References

Bastille, J. V., & Gill-Body, K. M. (2004). A yoga-based exercise program for people with chronic poststroke hemiparesis. *Phys Ther, 84*(1), 33-48.

Bianchi, G., Cavenago, C., & Marchese, M. (2004). Can the practice of yoga be dangerous? Considerations over a case of epiphyseal separation of the distal tibia in a teenager. *Journal of Orthopaedics and Traumatology, 5*(3), 188-190.

Birkel, D. A., & Edgren, L. (2000). Hatha yoga: Improved vital capacity of college students. *Alternative Therapies in Health and Medicine, 6*(6), 55-63.

Brown, K. D., Koziol, J. A., & Lotz, M. (2008). A Yoga-Based Exercise Program to Reduce the Risk of Falls in Seniors: A Pilot and Feasibility Study. *Journal of Alternative & Complementary Medicine, 14*(5), 454-457.

Carlson, L. E., Speca, M., Patel, K. D., & Goodey, E. (2004). Mindfulness-based stress reduction in relation to quality of life, mood, symptoms of stress and levels of cortisol, dehydroepiandrosterone sulfate (DHEAS) and melatonin in breast and prostate cancer outpatients. *Psychoneuroendocrinology, 29*(4), 448-474.

Chandler, J. M., Duncan, P. W., Sanders, L., & Studenski, S. (1996). The fear of falling syndrome: relationship to falls, physical performance, and activities of daily living in frail older persons. *Topics in Geriatric Rehabilitation, 11*(3), 55-63.

Chang, A., Hayes, K., Dunlop, D., Song, J., Hurwitz, D., Cahue, S., & Sharma, L. (2005). Hip abduction moment and protection against medial tibiofemoral osteoarthritis progression. *Arthritis & Rheumatism, 52*(11), 3515-3519.

Clay, C. C., Lloyd, L. K., Walker, J. L., Sharp, K. R., & Pankey, R. B. (2005). The metabolic cost of hatha yoga. *J Strength Cond Res, 19*(3), 604-610.

Cohen, J. (1992). A power primer. *Psychol Bull, 112*(1), 155-159.

Collins, C. (1998). Yoga: intuition, preventive medicine, and treatment. *JOGNN: Journal of Obstetric, Gynecologic & Neonatal Nursing, 27*(5), 563-568.

Coulter, H. D. (2001). *Anatomy of Hatha Yoga: a manual for students, teachers, and practitioners*: Body and Breath.

Cowen, V. S., & Adams, T. B. (2005). Physical and perceptual benefits of yoga asana practice: Results of a pilot study. *J Bodyw Mov Ther, 9*(3), 211-219.

Cowen, V. S., & Adams, T. B. (2007). Heart rate in yoga asana practice: A comparison of styles. *J Bodyw Mov Ther, 11*(1), 91-95.

Davies, G. J., Wallace, L. A., & Malone, T. (1980). Mechanisms of Selected Knee Injuries. *Physical Therapy, 60*(12), 1590-1595.

Delbaere, K., Crombez, G., Vanderstraeten, G., Willems, T., & Cambier, D. (2004). Fear-related avoidance of activities, falls and physical frailty. A prospective community-based cohort study. *Age & Ageing, 33*(4), 368-373.

Deyo, R. A., Mirza, S. K., & Martin, B. I. (2006). Back pain prevalence and visit rates: estimates from U.S. national surveys, 2002. *Spine (Phila Pa 1976), 31*(23), 2724-2727.

DiBenedetto, M., Innes, K. E., Taylor, A. G., Rodeheaver, P. F., Boxer, J. A., Wright, H. J., & Kerrigan, D. C. (2005). Effect of a gentle iyengar yoga program on gait in the elderly: An exploratory study. *Archives of Physical Medicine and Rehabilitation, 86*(9), 1830-1837.

DiCarlo, L. J., Sparling, P. B., Hinson, B. T., Snow, T. K., & Rosskopf, L. B. (1995). Cardiovascular, metabolic, and perceptual responses to Hatha Yoga standing poses. *Medicine, Exercise, Nutrition & Health, 4*(2), 107-112.

Dorociak, R. D., & Cuddeford, T. J. (1995). Determining 3-D system accuracy for the VICON 370 system. *Gait Posture, 3*(2), 88.

Fishman, L., Saltonstall, E., & Genis, S. (2009). Understanding and Preventing Yoga Injuries. *Int J Yoga Therap, 19*(-1), 47-53.

Galantino, M. L., Bzdewka, T. M., Eissler-Russo, J. L., Holbrook, M. L., Mogck, E. P., Geigle, P., & Farrar, J. T. (2004). The impact of modified hatha yoga on chronic low back pain: a pilot study. *Alternative Therapies in Health & Medicine, 10*(2), 56-59.

Garfinkel, M., & Schumacher, H. R., Jr. (2000). Yoga. *Rheum Dis Clin North Am, 26*(1), 125-132, x.

Garfinkel, M. S., Schumacher Jr, H. R., Husain, A., Levy, M., & Reshetar, R. A. (1994). Evaluation of a yoga based regimen for treatment of osteoarthritis of the hands. *Journal of Rheumatology, 21*(12), 2341-2343.

Garfinkel, M. S., Singhal, A., Katz, W. A., Allan, D. A., Reshetar, R., & Schumacher Jr, H. R. (1998). Yoga-based intervention for carpal tunnel syndrome: A randomized trial. *Journal of the American Medical Association, 280*(18), 1601-1603.

Greendale, G. A., McDivit, A., Carpenter, A., Seeger, L., & Mei-Hua, H. (2002). Yoga for Women With Hyperkyphosis: Results of a Pilot Study. *Am J Public Health, 92*(10), 1611-1614.

Hagins, M., & Khalsa, S. B. (2012). Bridging yoga therapy and scientific research. *Int J Yoga Therap*(22), 5-6.

Hagins, M., Moore, W., & Rundle, A. (2007). Does practicing hatha yoga satisfy recommendations for intensity of physical activity which improves and maintains health and cardiovascular fitness? *BMC Complement Altern Med, 7*, 40.

Harris, G. F., Smith, P. A., Medicine, I. E. i., & Conference, B. S. (1996). *Human motion analysis: current applications and future directions*: Institute of Electrical and Electronics Engineers.

Hart, C. E. F., & Tracy, B. L. (2008). Yoga as steadiness training: effects on motor variability in young adults. *Journal of Strength & Conditioning Research (Lippincott Williams & Wilkins), 22*(5), 1659-1669.

Hart, L. G., Deyo, R. A., & Cherkin, D. C. (1995). Physician Office Visits for Low Back Pain: Frequency, Clinical Evaluation, and Treatment Patterns From a U.S. National Survey. *Spine, 20*(1), 11-19.

Haslock, I., Monro, R., Nagarathna, R., Nagendra, H. R., & Raghuram, N. V. (1994). Measuring the effects of yoga in rheumatoid arthritis. *Br J Rheumatol, 33*(8), 787-788.

Hayes, M., & Chase, S. (2010). Prescribing yoga. *Primary Care: Clinics in Office Practice, 37*(1), 31-47.

Herrick, C. M., & Ainsworth, A. D. (2000). Invest in yourself. Yoga as a self-care strategy. *Nurs Forum, 35*(2), 32-36.

Hilliard, M. J., Martinez, K. M., Janssen, I., Edwards, B., Mille, M. L., Zhang, Y., & Rogers, M. W. (2008). Lateral balance factors predict future falls in community-living older adults. *Arch Phys Med Rehabil, 89*(9), 1708-1713.

Hong, Y., & Bartlett, R. (2010). *Routledge Handbook of Biomechanics and Human Movement Science*: Routledge.

Horak, F. B. (2006). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing, 35*(suppl 2), ii7-ii11.

Hu, M.-H., & Woollacott, M. H. (1994). Multisensory training of standing balance in older adults: I. Postural stability and one-leg stance balance. *Journal of gerontology, 49*(2), M52-M61.

Ives, J. C., & Sosnoff, J. (2000). Beyond the mind-body exercise hype. *Phys Sportsmed, 28*(3), 67-81.

Iyengar, B. K. S. (1982). *The concise light on yoga: yoga dipika*: Schocken Books.

Jagodzinski, M., Richter, G. M., & Pässler, H. H. (2000). Biomechanical analysis of knee hyperextension and of the impingement of the anterior cruciate ligament: a cinematographic MRI study with impact on tibial tunnel positioning in anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 8*(1), 11-19.

Jevsevar, D. S., Riley, P. O., Hodge, W. A., & Krebs, D. E. (1993). Knee kinematics and kinetics during locomotor activities of daily living in subjects with knee arthroplasty and in healthy control subjects. *Phys Ther, 73*(4), 229-239; discussion 240-222.

Johnson, M. E., Mille, M. L., Martinez, K. M., Crombie, G., & Rogers, M. W. (2004). Age-related changes in hip abductor and adductor joint torques. *Arch Phys Med Rehabil, 85*(4), 593-597.

Judge, J. O., Davis, R. B., 3rd, & Ounpuu, S. (1996). Step length reductions in advanced age: the role of ankle and hip kinetics. *J Gerontol A Biol Sci Med Sci, 51*(6), M303-312.

Judge, J. O., Ounpuu, S., & Davis, R. B., 3rd. (1996). Effects of age on the biomechanics and physiology of gait. *Clin Geriatr Med, 12*(4), 659-678.

Kaminoff, L. *Yoga Anatomy*: Human Kinetics.

Kean, C. O., Bennell, K. L., Wrigley, T. V., & Hinman, R. S. (2015). Relationship between hip abductor strength and external hip and knee adduction moments in medial knee osteoarthritis. *Clinical Biomechanics, 30*(3), 226-230.

Kerrigan, D. C., Todd, M. K., Della Croce, U., Lipsitz, L. A., & Collins, J. J. (1998). Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Arch Phys Med Rehabil, 79*(3), 317-322.

Kirk, M., & Boon, B. (2006). *Hatha Yoga Illustrated*: Human Kinetics.

Kirk, R. E. (2007). Effect magnitude: A different focus. *Journal of Statistical Planning and Inference, 137*(5), 1634-1646.

Law, N. H. (2013). *Kinematics & kinetics analysis of the lower extremity of normal weight, overweight, and obese individuals during stair ascent & descent.* (Master's Thesis), University of Ottawa, Ottawa.

Law, N. Y. (2011). *Kinetics and kinematics of the lower extremity during performance of two typical Tai Chi movements by the elders.* (Master's degree), University of Ottawa, Ottawa.

Law, N. Y., & Li, J. X. (2014). The temporospatial and kinematic characteristics of typical Tai Chi movements: Repulse Monkey and Wave-hand in Cloud. *Res Sports Med, 22*(2), 111-123.

Leardini, A., Chiari, L., Della Croce, U., & Cappozzo, A. (2005). Human movement analysis using stereophotogrammetry. Part 3. Soft tissue artifact assessment and compensation. *Gait Posture, 21*(2), 212-225.

Lee, S. (2011). *Combined effects of high-heeled shoes and load carriage on gait and posture in young healthy women.* (Master's Thesis), University of Ottawa, Ottawa.
Lord, S. R., Rogers, M. W., Howland, A., & Fitzpatrick, R. (1999). Lateral stability, sensorimotor function and falls in older people. *J Am Geriatr Soc, 47*(9), 1077-1081.
Lord, S. R., Ward, J. A., & Williams, P. (1996). Exercise effect on dynamic stability in older women: A randomized controlled trial. *Archives of Physical Medicine and Rehabilitation, 77*(3), 232-236.
Maki, B. E., Edmondstone, M. A., & McIlroy, W. E. (2000). Age-related differences in laterally directed compensatory stepping behavior. *J Gerontol A Biol Sci Med Sci, 55*(5), M270-277.
Manjunath, N. K., & Telles, S. (2001). Improved performance in the Tower of London test following yoga. *Indian Journal of Physiology and Pharmacology, 45*(3), 351-354.
Mao, D. W., Li, J. X., & Hong, Y. (2006). The duration and plantar pressure distribution during one-leg stance in Tai Chi exercise. *Clin Biomech (Bristol, Avon), 21*(6), 640-645.
Medicine, A. C. o. S., Franklin, B. A., Whaley, M. H., Howley, E. T., & Balady, G. J. (2000). *ACSM's guidelines for exercise testing and prescription*: Lippincott Williams & Wilkins.
Miyazaki, T., Wada, M., Kawahara, H., Sato, M., Baba, H., & Shimada, S. (2002). Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Annals of the Rheumatic Diseases, 61*(7), 617-622.
Morgan, P. M., LaPrade, R. F., Wentorf, F. A., Cook, J. W., & Bianco, A. (2010). The Role of the Oblique Popliteal Ligament and Other Structures in Preventing Knee Hyperextension. *The American Journal of Sports Medicine, 38*(3), 550-557.
Mueller, D. (2002). Yoga Therapy. *ACSM's Health & Fitness Journal, 6*(1), 18&hyhen;24.
Mueller, M. J., Minor, S. D., Sahrmann, S. A., Schaaf, J. A., & Strube, M. J. (1994). Differences in the Gait Characteristics of Patients With Diabetes and Peripheral Neuropathy Compared With Age-Matched Controls. *Physical Therapy, 74*(4), 299-308.
Murugesan, R., Govindarajulu, N., & Bera, T. K. (2000). Effect of selected yogic practices on the management of hypertension. *Indian Journal of Physiology and Pharmacology, 44*(2), 207-210.
Nordin, M., & Frankel, V. H. (2001). *Basic Biomechanics of the Musculoskeletal System*: Lippincott Williams & Wilkins.
Omkar, S. N., Mour, M., & Das, D. (2011). A mathematical model of effects on specific joints during practice of the Sun Salutation - A sequence of yoga postures. *Journal of Bodywork and Movement Therapie, 15*(2), 201-208.
Patel, S. C., & Parker, D. A. (2008). Isolated rupture of the lateral collateral ligament during yoga practice: a case report. *J Orthop Surg (Hong Kong), 16*(3), 378-380.
Paterson, D. H., Jones, G. R., & Rice, C. L. (2007). Ageing and physical activity: evidence to develop exercise recommendations for older adults. *Canadian Journal of Public Health, 98*, S69-108.
Perry, J. (1992). *Gait Analysis: Normal and Pathological Function*: SLACK.
Prasad, K. V. V., Ramana, Y. V., Raju, P. S., Reddy, M. V., & Murthy, K. J. R. (2001). ENERGY COST AND PHYSIOLOGICAL EFFICIENCY IN MALE YOGA PRACTITIONERS. *Journal of Exercise Physiology Online, 4*(3), 38-44.

Radin, E. L., Yang, K. H., Riegger, C., Kish, V. L., & O'Connor, J. J. (1991). Relationship between lower limb dynamics and knee joint pain. *J Orthop Res, 9*(3), 398-405.
Rai, L., Ram, K., Kant, U., Madan, S., & Sharma, S. (1994). Energy expenditure and ventilatory responses during Siddhasana--a yogic seated posture. *Indian J Physiol Pharmacol, 38*(1), 29 - 33.
Raju, P. S., Kumar, K. A., Reddy, S. S., Madhavi, S., Gnanakumari, K., Bhaskaracharyulu, C., . . . et al. (1986). Effect of yoga on exercise tolerance in normal healthy volunteers. *Indian J Physiol Pharmacol, 30*(2), 121-132.
Raju, P. S., Prasad, K. V. V., Venkata, R. Y., Murthy, K. J. R., & Reddy, M. V. (1997). Influence of intensive yoga training on physiological changes in 6 adult women: A case report. *Journal of Alternative and Complementary Medicine, 3*(3), 291-295.
Raub, J. A. (2002). Psychophysiologic effects of Hatha Yoga on musculoskeletal and cardiopulmonary function: a literature review. *J Altern Complement Med, 8*(6), 797-812.
Reinschmidt, C., van den Bogert, A. J., Nigg, B. M., Lundberg, A., & Murphy, N. (1997). Effect of skin movement on the analysis of skeletal knee joint motion during running. *J Biomech, 30*(7), 729-732.
Richards, J. G. (1999). The measurement of human motion: A comparison of commercially available systems. *Human Movement Science, 18*(5), 589-602.
Robertson, D. G. E. (1997). *Introduction to Biomechanics for Human Motion Analysis* (Second ed. ed.): Waterloo Biomechanics.
Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. N. (2004). *Research Methods in Biomechanics*. United States: Human Kinetics.
Roland, K. P., Jakobi, J. M., & Jones, G. R. (2011). Does Yoga Engender Fitness in Older Adults? A Critical Review. *Journal of Aging & Physical Activity, 19*(1), 62-79.
Runge, C. F., Shupert, C. L., Horak, F. B., & Zajac, F. E. (1999). Ankle and hip postural strategies defined by joint torques. *Gait Posture, 10*(2), 161-170.
Schmid, A. A., Van Puymbroeck, M., & Koceja, D. M. (2010). Effect of a 12-week yoga intervention on fear of falling and balance in older adults: a pilot study. *Arch Phys Med Rehabil, 91*(4), 576-583.
Shephard, R. J., Berridge, M., & Montelpare, W. (1990). On the Generality of the “Sit and Reach” Test: An Analysis of Flexibility Data for an Aging Population. *Research Quarterly for Exercise and Sport, 61*(4), 326-330.
Sherman, K. J., Cherkin, D. C., Cook, A. J., Hawkes, R. J., Deyo, R. A., Wellman, R., & Khalsa, P. S. (2010). Comparison of yoga versus stretching for chronic low back pain: protocol for the Yoga Exercise Self-care (YES) trial. *Trials, 11*, 36.
Silver, T., & Butcher Mokha, M. (2005). Effects of 6 weeks of yoga training on selected measures of static and dynamic balance. *ISBS - Conference Proceedings*, 679 - 683.
Teichtahl, A. J., Wluka, A. E., & Cicuttini, F. M. (2008). Frontal plane knee alignment is associated with a longitudinal reduction in patella cartilage volume in people with knee osteoarthritis. *Osteoarthritis and Cartilage, 16*(7), 851-854.
Teixeira-Salmela, L. F., Nadeau, S., McBride, I., & Olney, S. J. (2001). Effects of muscle strengthening and physical conditioning training on temporal, kinematic and kinetic variables during gait in chronic stroke survivors. *J Rehabil Med, 33*(2), 53-60.
Tekur, P., Nagarathna, R., Chametcha, S., Hankey, A., & Nagendra, H. R. (2012). A comprehensive yoga programs improves pain, anxiety and depression in chronic

low back pain patients more than exercise: an RCT. *Complement Ther Med, 20*(3), 107-118.

Telles, S., Nagarathna, R., Nagendra, H. R., & Desiraju, T. (1993). Physiological changes in sports teachers following 3 months of training in Yoga. *Indian J Med Sci, 47*(10), 235-238.

Terada, M., Wagatsumal, A., & Kraemer, W. J. (1997). Influence of Passive Torque Offered by Soft Tissue on Oxygen Consumption During Movement in Men and Women. *The Journal of Strength & Conditioning Research, 11*(4), 214-218.

Tran, M. D., Holly, R. G., Lashbrook, J., & Amsterdam, E. A. (2001). Effects of Hatha Yoga Practice on the Health-Related Aspects of Physical Fitness. *Prev Cardiol, 4*(4), 165-170.

Uhlig, T. (2012). Tai Chi and yoga as complementary therapies in rheumatologic conditions. *Best Pract Res Clin Rheumatol, 26*(3), 387-398.

Van Puymbroeck, M., Payne, L. L., & Pei-Chun, H. (2007). A Phase I Feasibility Study of Yoga on the Physical Health and Coping of Informal Caregivers. *Evidence-based Complementary & Alternative Medicine (eCAM), 4*(4), 519-529.

Wang, M. Y., Flanagan, S. P., Song, J. E., Greendale, G. A., & Salem, G. J. (2006). Relationships among body weight, joint moments generated during functional activities, and hip bone mass in older adults. *Clin Biomech (Bristol, Avon), 21*(7), 717-725.

Westwell, M., Bell, K., & Õunpuu, S. (2006). Evaluation of lower extremity joint moments experienced during several yoga postures. *Gait & Posture, 24, Supplement 2*(0), S213-S215.

Whipple, R., Wolfson, L., & Amerman, P. (1987). The relationship of knee and ankle weakness to falls in nursing home residents: an isokinetic study. *Journal of the american geriatrics society, 35*(1), 13-20.

Whipple, R. H., Wolfson, L. I., & Amerman, P. M. (1987). The relationship of knee and ankle weakness to falls in nursing home residents: an isokinetic study. *J Am Geriatr Soc, 35*(1), 13-20.

Williams, K. A., Petronis, J., Smith, D., Goodrich, D., Wu, J., Ravi, N., . . . Steinberg, L. (2005). Effect of Iyengar yoga therapy for chronic low back pain. *Pain, 115*(1-2), 107-117.

Winter, D. A. (2004). *Biomechanics and Motor Control of Human Movement*: John Wiley & Sons.

Winters, D. A. (1991). *The Biomechanics and Motor Control of Humain Gait: Normal, elderly, and Pathological* (Second ed. ed.). Waterloo.

Wood, C. (1993). Mood change and perceptions of vitality: A comparison of the effects of relaxation, visualization and yoga. *Journal of the Royal Society of Medicine, 86*(5), 254-258.

Wood, G. A. (1982). Data smoothing and differentiation procedures in biomechanics. *Exerc Sport Sci Rev, 10*, 308-362.

Wu, G., & Hitt, J. (2005). Ground contact characteristics of Tai Chi gait. *Gait Posture, 22*(1), 32-39.

Wu, G., & Millon, D. (2008). Joint kinetics during Tai Chi gait and normal walking gait in young and elderly Tai Chi Chuan practitioners. *Clin Biomech (Bristol, Avon), 23*(6), 787-795.

Yamada, H., Koshino, T., Sakai, N., & Saito, T. (2001). Hip Adductor Muscle Strength in Patients With Varus Deformed Knee. *Clinical Orthopaedics and Related Research, 386*, 179-185.

Appendix A – Plug-in-Gait Marker Placement Set

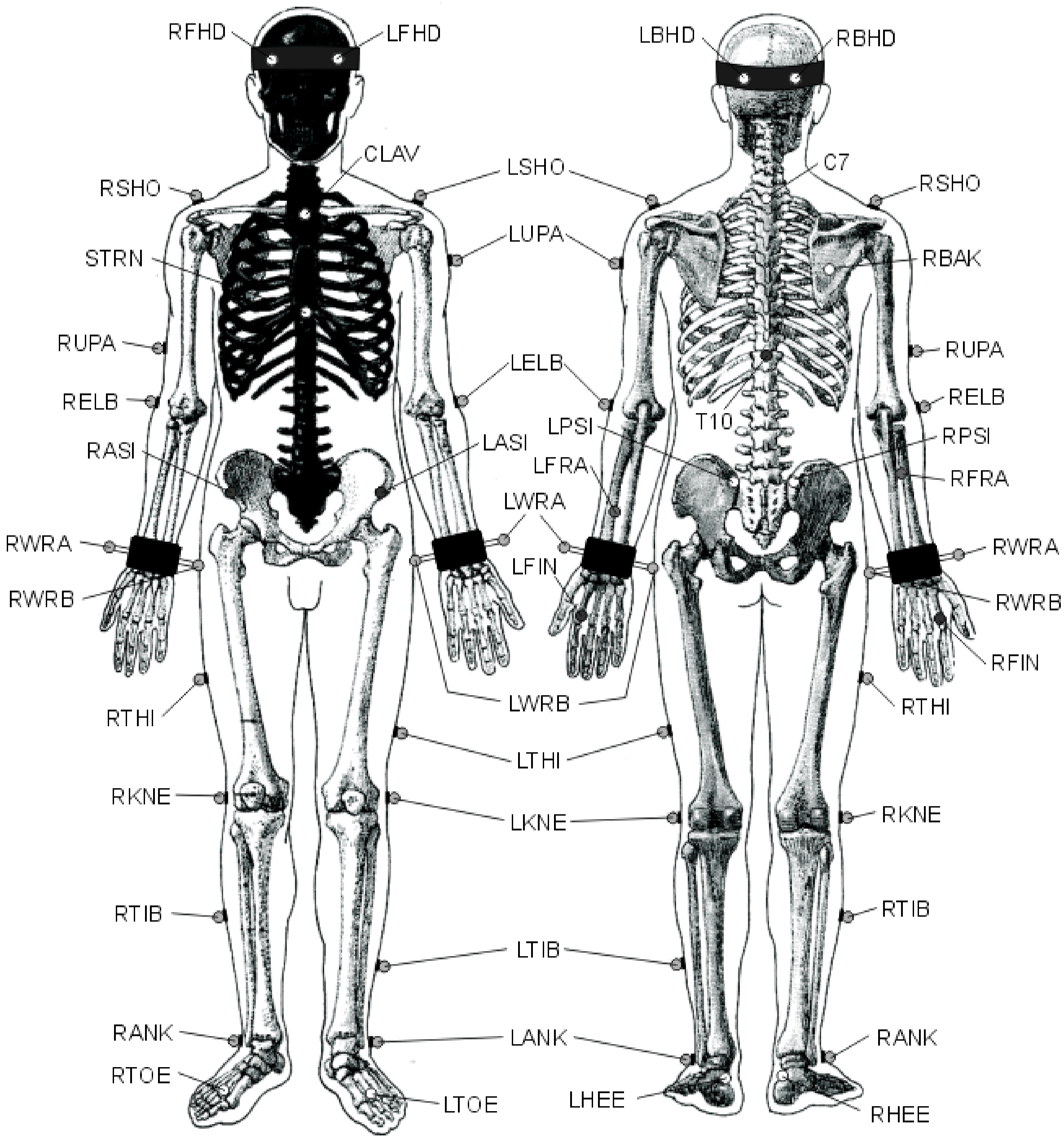

Figure 19 Schematic representation of the Plug-in-Gait market placement set.

Table 30 Plug-in-Gait markers and their respective acronym and description used in this study. Description indicates the bony landmark that was used for marker placement. The use of "L" and "R" represent the left and right, respectively.

Head	
LFHD & RFHD	Temple
LBHD & RBHD	Back of head
Torso	
C7	7th cervical vertebrae
T10	10th thoracic vertebrae
CLAV	Jugular notch
STRN	Xiphoid process
RBAK	Middle of right scapula
Arms	
LSHO & RSHO	Acromio-clavicular joint
LUPA & RUPA	Upper arm
LELB & RELB	Lateral epicondyle
LFRA & RFRA	Forearm
LWRA & RWRA	Wrist bar thumb side
LWRB & RWRB	Wrist bar pinkie side
LFIN & RFIN	Dorsum of the hand head of the 2nd metacarpal
Pelvis	
LASI & RASI	Anterior superior iliac crest
LPSI & RPSI	Posterior superior iliac crest
Legs	
LTHI & RTHI	Lateral thigh
LMKN & RMKN	Medial epicondyle of the knee
LKNE & RKNE	Lateral epicondyle of the knee
LTIB & RTIB	Lateral shank
LANK & RANK	Lateral malleolus
LMAN & RMAN	Medial malleolus
Feet	
LTOE & RTOE	2nd metatarsal head of foot
LHEE & RHEE	Posterior calcaneus

Appendix B – Yoga Practice Frequency Questionnaire

uOttawa

Université d'Ottawa | University of Ottawa

Faculte des sciences de la sante Faculty of Health Sciences
Ecole des sciences de l'activite physique School of Human Kinetics

Yoga practice frequency questionnaire

1. What year did you start practicing yoga? ___________

2. What year did you complete your 200 hour Yoga Teacher Training (YTT)? ___________

3. What style was you YTT? ___________

4. Was your YTT Yoga Alliance certified? Y / N

5. What is/are your preferred style of Asana Yoga practice? Please specify how long have you practiced it.

   a. Ananda
   b. Anusara
   c. Ashtanga
   d. Bikram
   e. Integral
   f. Iyengar
   g. Kripalu
   h. Kundalini
   i. Restorative
   j. Sivananda
   k. Viniyoga
   l. Hatha (non-specific)
   m. Other: __________________

6. Does this style include stepping forward from Downward Dog to standing postures?

   Y / N

7. How often do you practice? ________/ week OR ________/month