Musculoskeletal Modeling and Analysis of Trikonasana

Abstract

Context: Yoga has origins speculated to date back to pre-Vedic Indian period and is practiced as a common exercise, both in India as well as all around the world. Although the yoga practices are ages old, there is not much research literature available. Moreover, with the advancement in technology, the modern analysis tools are not used up to their full potential. **Aims:** This research focuses on developing a framework for analyzing trikonasana, using the optical motion capture system, and validating the noninvasive method for analyzing muscle activity in prominent muscles while performing trikonasana. **Subjects and Methods:** We have adopted the noninvasive analysis method using optical motion capture system OptiTrack™ for recording the human motion and musculoskeletal modeling software LifeMod™ to analyze the muscle activity while performing trikonasana. Surface electromyography (sEMG) studies were performed using Trigno™ (Delsys Inc.) wireless sEMG sensors to validate the LifeMod simulation results pertaining muscle activation. **Results:** It was observed that the characteristics of the sEMG match to that of the estimated muscle tension from the architecture used in this study. The muscle groups such as external right obliques muscles, rectus abdominis of the front leg, and gluteus maximus and gluteus medius of the rear leg were observed to undergo major activation during an isometric contraction while performing trikonasana. The magnitudes of the muscle tension during the left bend depict a close resemblance to the muscle tension magnitudes during the right bend. **Conclusions:** The optical motion capture system and musculoskeletal modeling software can be used to analyze muscle activity in any yoga exercise noninvasively. Since the yoga exercises majorly require the practitioner to maintain a certain posture for a considerable duration, our approach can be used to find the important muscles involved and their corresponding muscle tension when they undergo isometric contraction.

Keywords: *Isometric contraction, LifeMod, musculoskeletal modeling, optical motion capture, trikonasana, yoga*

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Introduction

The word yoga is derived from the Sanskrit word *yuj* meaning union. Yoga utilizes mental and physical exercises to attain samadhi or the union of the individual self with the infinite.[1] The regular practice of yoga helps establish natural harmony between various organs of the body. This, in turn, helps maintain the well-being of the individual. The origin of yoga though a highly debated topic could be traced back since the evolution of the Indus Valley civilization, as a typical Indian cultural phenomenon, firmly rooted in the society.[2,3] Since then yoga has undergone several variations in the style of practice pertaining to there are four major periods or generations of various styles of yoga practised; Vedic, Pre-Classical, Classical and Post-Classical.[4,5]

Yoga is a broad concept involving various physical, mental, and spiritual practices. The most popular among all yoga asanas is the Hatha Yoga. Some historians claim the emergence of Hatha yoga practice predates even before the 11th century and sheds its persistence over following a proper exercise routine while maintaining specific body postures (asanas).[6] During the late 20th century, the practice of Hatha yoga was highly popularized in the Western world by Iyengar.

Trikonasana, an asana in Hatha Yoga, largely focuses on the lateral bend-stretching, resulting from the wider spacing of the feet. Performing trikonasana, while maintaining the perfect posture largely influences the lateral spinal mobility, elongates the leg muscles, and removes stiffness in the legs and hips.[7,8] Performing any yogasana (especially trikonasana) is

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governed by step-wise body posture maintenance and stability which are the significant factors.

The yoga asanas are usually taught by the practioners who learned from their predecessors, who seldomly have tried to step outside of the tradition and look at yoga from a research point of view. The start of 21st century saw more of elaborate scientific research focused toward the positive aspects of performing yoga for various diseases and body pain and results delivered show yoga as a relatively safer form of exercise, capable of increasing strength, flexibility, balance, and functional endurance of people in good health conditions and also those with musculoskeletal affliction.[9-11] Ni *et al*. analyzed 11 yoga postures from Vinyasa yoga for trunk and hip muscles.[12] Longpré *et al*. primarily compared the muscle activation of the thigh muscles in various standing poses, one of which being trikonasana.[13] In one study, the authors have used electromyography (EMG) to analyze and compare abdominal muscles activity while doing breathing yoga exercise versus traditional curls.[14] Salem *et al*. proposed one of the first biomechanical analysis methods while performing Hatha yoga using motion capture system integrated with surface EMG (sEMG) to quantify the physical demands of performing the asanas and evaluating joint angles, muscle activation levels, etc., for various Hatha yoga postures.[15]

Although the sEMG sensors have been used to study the muscle activation patterns, it has a couple of demerits to its account. The sEMG can give the insights of the superficial muscles only. The human body is prone to the phenomenon of perspiration under high temperature or humid conditions, which can lead to sliding of the sEMG sensors and eventually falling-off the skin. Excessive fat deposition in the body can hinder the results of the sEMG sensors.[16] Moreover, they are prone to noise and often mixed up with other muscle signals.[17] The solution for this is to use inverse dynamic algorithms developed in robotics to obtain the joint torques of the skeleton and then run numerical optimization to compute the muscle tensions.[18] Here, the joint torques are computed from the motion data and the geometric and inertial parameters of the skeleton model, and the mathematical optimization with physiologically appropriate criteria, for example, minimizing the signal-dependent noise, distributes them to the muscle tensions.[19] The motion data can be captured by various methods one of which is optical motion capture. The notion of motion capture system was primarily intended for research applications in the field of computer vision, computer-generated imagery, and motion planning in robotics. However, recent developments in the field of biomechanical research have witnessed marker-based optical motion capture system as a noninvasive and highly valuable tool for recording and analyzing of the human motion, particularly pertaining to sports and rehabilitation studies.[20,21] One of the reasons for using the optical motion capture system in biomechanical studies is the ease of interfacing the acquired human motion data with different musculoskeletal modeling software (such as OpenSim, Adams LifeMod, etc.,) for analyzing human gait patterns, kinematics, dynamics, and determination of various associated parameters such as muscle activation and joint torques and angles.[22] In the field of sports-rehabilitation sciences, optical motion capture has been extensively used as a medium of recording and analyzing the motion patterns of the subjects.[23] Although previously there have been experimental studies conducted on various yogasana based on sEMG which involves integrating inertial measurement unit, accelerometer,[24] or gyroscope-based sensors, very few have taken the approach of the utilization of optical motion capture system as a means of data acquisition. Moreover, since body posture is very critical in yoga, optical motion capture system can be very useful to capture full body to check proper alignment.

Hill type muscle model

The hill-type muscle consists of three elements and is used to depict the mechanical muscle response.[25-27] The major components of this model include the contractile element (CE), in series with the series elastic element, and parallel with the parallel elastic (PE) element depicted in Figure 1. The CE is responsible for generating the active whereas the passive element determines the passive elastic properties of the muscle fiber.[28]

The hill equation formulates that F_{muscle} generated is the aggregate of passive element force (F_{PE}) and the CE force (F_{CE}) while ignoring the SEE shown in equation (1).[29] The CE (also known as an active element) is dependent on instantaneous muscle length (l_{ist}), instantaneous muscle shortening velocity, and activation state (A [t]) which is a function of time in equation (2). The passive element is the function of l_{ist}.

$$F_{Muscle} = F_{CE} + F_{PE} \quad (1)$$

The contractile elemental force (F_{CE}) is computed based on equation (2), which models the active muscle behavior with normalized activation state and a maximum F_{muscle} at activation. It is essentially dependent on the force-length (f_V) and force-velocity relation (f_L).[28,30]

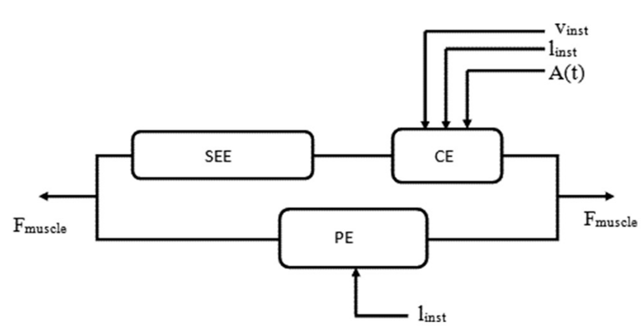

Figure 1: Hill type muscle model

$F_{CE} = A(t).\ F_{max}.\ f_V.\ (v_l).\ f_L.\ (l_l)$ (2)

Where, A (t) = Activation state which is normalized between the resting state, 0 to the maximum activation state, 1.

F_{max} is F_{muscle} at maximum activation isometric conditions.

f_V is the normalized active force-velocity relation (based on hill-curve).

f_L is the normalized active force-length relation.

v_l is the dimensionless lengthening velocity.

l_l is dimensionless muscle length.

The F_{PE} is modeled based on the product of passive muscle stress (σ) and physiological cross-sectional area (pCSA) of the specific muscle equation (3). The nonlinear stress-strain relationship is used to model the passive muscle stress.[31]

$F_{PE} = \sigma.\ pCSA$ (3)

Following literature survey, analysis of muscle activity while performing trikonasana using noninvasive techniques was considered necessary. Trikonasana has been considered specifically for the current study because of its simple geometry through which all the aspects of the study can be illustrated and detectability of all the markers by the motion capture cameras while performing the exercise and the isometric nature of performing the asana.

Hence, the current study was undertaken to create an architecture for biomechanical analysis of the subject performing trikonasana using optical motion capture system OptiTrack™ and musculoskeletal modeling and simulation using LifeMod. In addition, information regarding key muscle groups recruited while performing the asana and hence elucidating the kinds of muscle groups strengthened was explored.

The clinical relevance of this study is to provide an initial basis for better prescription of Trikonasana as a physical therapy to better recruit trunk and thigh muscles and also as a biofeedback tool to assist training and rehabilitation.

Subjects and Methods

Participant

The study was performed at the Biomechanics Laboratory, Indian Institute of Science (IISc), Bangalore. One healthy male subject of age 56 years, with a height of 165 cm and weight 64 kg with prior experience and practice for 30 years in the field of yoga was selected. The subject gave a written consent of his willingness to participate in this experiment, verified by the Human Ethics Committee, IISc.

Procedure

The exercise was performed in the following protocols in the gait cycle of the trikonasana as depicted in Figure 2.

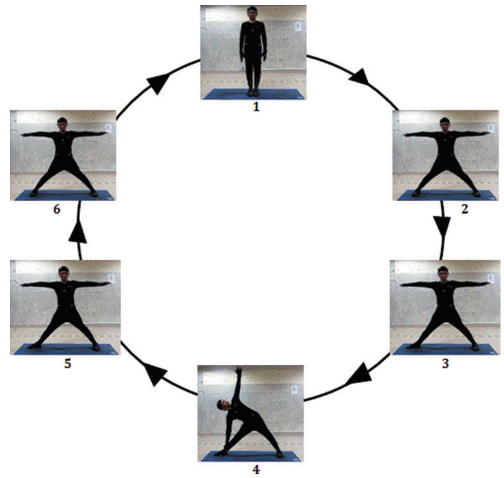

Figure 2: Steps involved in trikonasana

1. Initially, the subject stood in an upright position (tadasana) maintaining around one-foot distance between the feet
2. Then, subject was instructed to raise both hands to shoulder level with palm facing the ground and stretch both legs to an extent of 3–4 feet
3. Subsequently, turning the right foot outward about 90°, while keeping the left foot rotated inward about 15° ensuring the direction of the right foot is to the center of the left foot
4. The subject bends the entire upper torso, laterally at 90° toward the right side, till the right-hand rests on the right shin bone
5. The left hand is held straight up
6. The head is turned gently upward and the gaze is set toward the tip of the left palm while ensuring that the legs, arms, and the torso are in the same plane. Both arms are maintained along the same straight line
7. The current posture is maintained for about 20 s, with normal breathing
8. After a time span of 20 s, the subject returns to the initial position while retaining the stretch, inhaling slowly and come up
9. Later, the same procedure is repeated, changing the side (i.e. left side).

Experimental setup

Motion capture data acquisition using OptiTrack motion capture system

OptiTrack™ motion capture system was used for biomechanical analysis. A total of eight infrared-optical motion capture cameras (OptiTrack Prime 13W, each sampling at 120 Hz) were used for motion tracking and recording. The software platform used was OptiTrack Motive. Optical motion capture system although effective in tracking human motion comes with a certain range of diminution. First, the optical cameras were calibrated, placing retro-reflective markers on the dark suit worn by the subject. As per marker placement protocols in OptiTrack Motive software, the standard Plug-In-Gait (39 markers) is adopted for the experiment, defining each body segments, head, torso, upper arms (left and right), upper hands, forearms, both upper and lower legs, and feet.[32,33] The 39-optical reflective markers, 12 on lower body, 23 along the upper body, and 4 on the head, are placed on the subject as shown in Figure 3. Based on the information from all the optical motion tracking cameras, the marker locations were determined and the subsequent three-dimensional (3D) motion trajectories are confirmed more were accurate.

Musculoskeletal modeling of the human body in LifeMOD

The optical motion capture data recorded through the OptiTrack Motive software was exported in the comma-separated values format file. The file mostly contains the marker position in mm and also the motion trajectory data. There are total of 117 position values, three (x, y, and z coordinates) for each marker position. These values were copied to the text files in the time-stamped format. A script compiled in python was used to accomplish this. The script also offsetted each value by the distance of the hip's COM location to translate the actual origin to the LifeMOD's origin which is at the center of the pelvis.

The 3D musculoskeletal model of the human body was generated through LifeMOD Biomechanics modeler, based on the subject's anthropometric data. The extent of the application of the LifeMOD/ADAMS in medical and sports research is commendable while analyzing the human body motion through generated models, simulations, and delivering a substantial amount of outputs.[34,35] Even in the field of yogasana, LifeMOD has been tremendously useful as a simulation tool for analyzing the human body dynamics.[26]

The musculoskeletal model of the subject in LifeMOD environment follows the closed hill type muscle model [Figure 4], with a group of main muscles that govern the rigorous motions of the body segments. After setting up the human model with LifeMOD, motion trajectory was imported and an inverse dynamic simulation was carried out by ADAMS. Before running the inverse dynamic simulation, the muscle tissue properties such as maximum allowable stress to each specific muscle and physiological cross-section area (pCSA) are assigned, from the GeBod anthropometric database. The spring-damper complexes' (muscles) contraction histories were recorded in the inverse dynamic simulation. Then, the motion driver was removed and the muscle contraction histories were employed to perform a forward dynamic simulation. During forward dynamic simulation, the trikonasana was performed by computer-generated human model to recreate the motion history and show the relationship between muscles force and body motion.

Surface electromyography

An important factor of this research was to determine the muscle tension during the extreme bending positions while performing trikonasana when isometric contraction takes place. From the previous studies, it can be inferred that there is a linear relationship between the muscle tension and sEMG. Therefore, the surface EMG techniques can be used in the current study to validate the results acquired from the LifeMod simulations. For the data acquisition, we used the Trigno™ wireless sEMG sensor, courtesy of Delsys Inc. The sensor was communicating wirelessly with a personal computer running the software, where the data were streamed and recorded.

Before attaching the sensors, the subject's skin was cleaned by swabbing it with 70% isopropyl alcohol. Double-sided adhesive interfaces tailored to match the contours of the sensors were applied on the sEMG sensors to allow it to stick to the skin. One wireless sEMG sensor was placed over the right external oblique muscle, located approximately 15 cm lateral and transverse to the umbilicus.[35] The sEMG sensor was kept on, during the full cycle of performing trikonasana. The sEMG sensor was switched-on before recording any data. sEMG data were simultaneously recorded while the subject was performing the exercise in the motion capture suit to maintain the sync between the two systems.

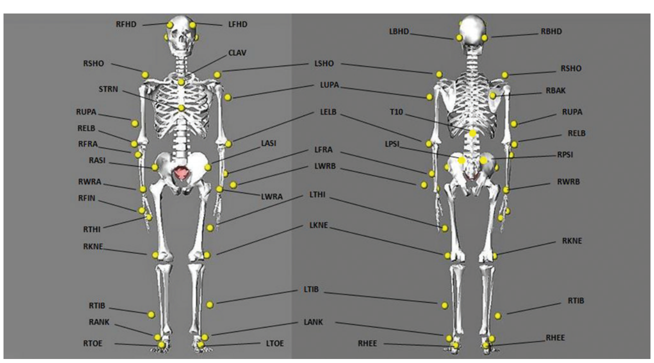

Figure 3: Plug-In-Gait marker set

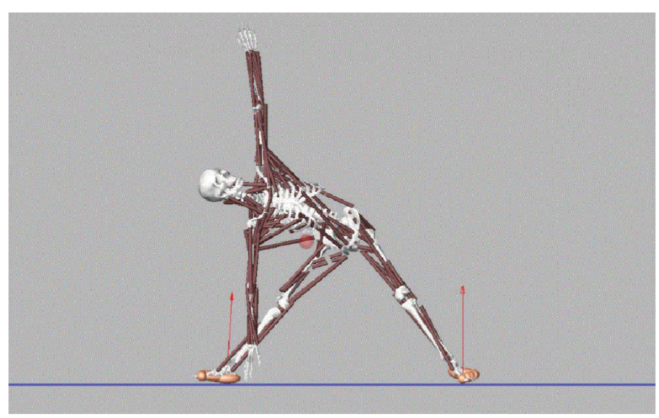

Figure 4: Musculoskeletal modeling in LifeMod

Results

The [Figures 5 and 6] show the muscle tension in the prominent muscles involved during right and left holding positions. It can be observed from the figures that the muscle groups such as obliques, rectus abdominis, and psoas major of the front leg and gluteus maximus and gluteus medius of the back leg undergo major activation during isometric contraction. We can see that the magnitudes of the muscle tension during the left bend, closely match the magnitudes during the right bend.

To validate the muscle tension estimated by the musculoskeletal model, sEMG was measured for muscle groups such as obliques. Various studies have shown that there is a linear relationship between F_{muscle} and EMG at isometric contraction.[4,36]

$$F = g_1E + \text{constant} \tag{4}$$

Where g is a constant gain factor and E is the mean rectified EMG.

Figure 7 is a plot of surface EMG root mean square (RMS) of right oblique during right bend and it can be observed that the characteristics of the EMG match to that of the estimated muscle tension as shown in Figure 8, from musculoskeletal modeling software LifeMod. Only the sEMG (RMS) data of the right oblique muscle groups during right bend are formulated because those are superficial muscle groups that delivered nearly accurate output compared to the ones from LifeMod.

Discussion

The primary purpose of our research was to investigate the application of optical motion capture and musculoskeletal modeling as a useful noninvasive tool to measure muscle activity while performing trikonasana. The linear relationship between F_{muscle} and sEMG during isometric contraction was positively confirmed by the results as illustrated in Figures 5 and 6. The architecture used in this study is very useful to understand what are the major muscles involved in performing any asana. For example, referring to the [Figures 5 and 6], it can be inferred that trunk and thigh muscles are majorly effected by maintaining the posture in trikonasana. One of the important benefits of knowing the behavior of muscles is that this allows better prescription of the asana as a physical therapy to better recruit trunk and thigh muscles. The other benefit of using this noninvasive architecture is to analyze not only the behavior of superficial muscles but also internal muscles such as psoas major.

This setup can very well be used to analyze muscle activity in any yoga exercise. Since the yoga exercises

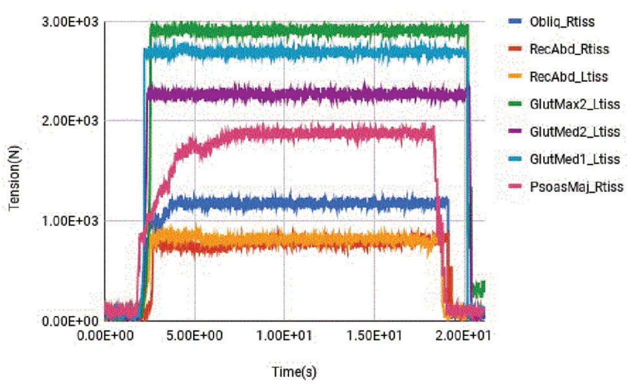

Figure 5: LifeMod estimation of muscle tensions during right bend isometric contraction

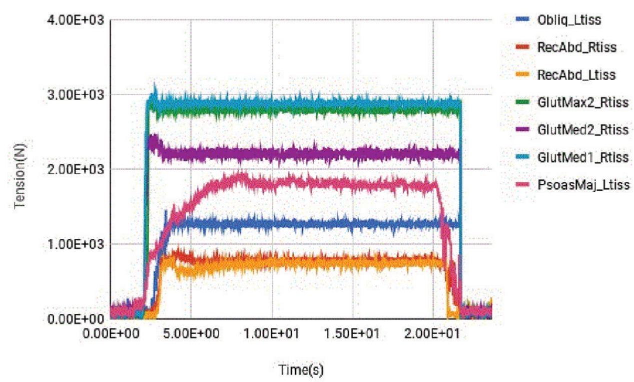

Figure 6: LifeMod estimation of muscle tensions during left bend isometric contraction

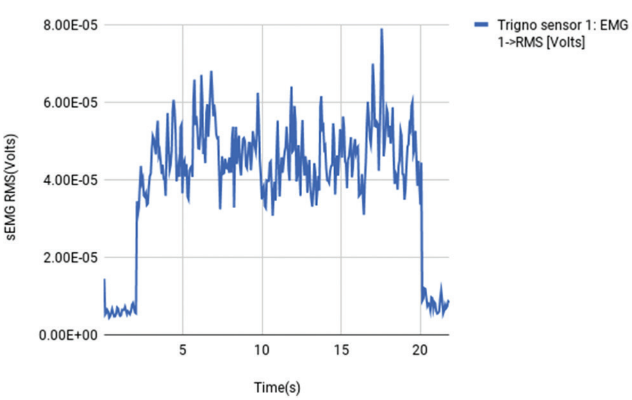

Figure 7: Surface electromyography (root mean square) of right oblique muscle at isometric contraction

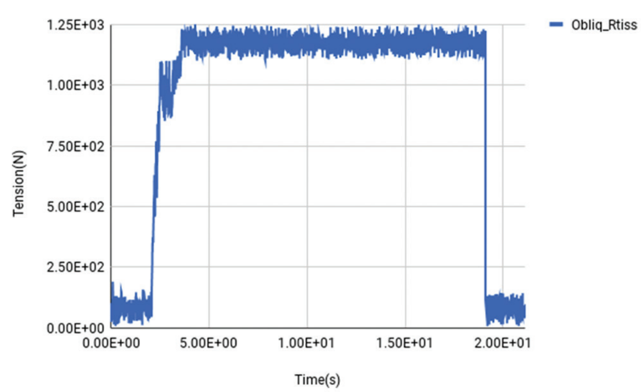

Figure 8: LifeMod estimation of muscle tension in right oblique muscle at isometric contraction

majorly require the practitioner to maintain a certain posture for a considerable duration, our approach can be used to find the important muscles involved and their corresponding muscle tension when they undergo isometric contraction. Although the current study primarily focuses on the muscle activity at the final postures, the illustrated setup can be used to capture the full cycle of the asanas, thereby facilitating the analysis of not only the muscle activity but also the nature of geometry involved. This is important to make sure the posture is correct. The execution of the yoga asana has to be very graceful. The dynamics of motion estimated by the musculoskeletal system can help identify any abrupt behavior in performing the asana.

In the future studies, the architecture of implementing optical motion capture could be extended towards various other yoga postures, which will be the main motivation for our future research efforts. Also providing a statistical analysis with a broader experimental sample size will be documented in the future works.

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Conflicts of interest

There are no conflicts of interest.

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