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EXERCISE PHYSIOLOGY

A mathematical model of effects on specific joints during practice of the Sun Salutation — A sequence of yoga postures

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Summary The 'Sun Salutation' consists of a sequence of ten yoga postures, each posture counteracting the preceding one producing a balance between flexion and extension, performed with synchronized breathing and aerobic activity. As this sequence is often performed and recommended by many yoga practitioners, there is a need for the development of a biomechanical model to support its reported clinical benefits. This requires a detailed knowledge of the nature of the forces and moments at the various joints involved. A simple mathematical model based on rigid body mechanics is developed for each of the Sun Salutation postures. Dynamic moments with high magnitudes and rates, applied with unusual distribution patterns, optimal for osteogenesis, are found to occur. Also, the joints are subjected to submaximal loadings thus ensuring that none of the joints are overstressed.

Introduction

Many metals, when combined appropriately and in the right proportion yield an alloy, which usually has novel properties. The best of orchestras is a harmonious combination of various instruments. Likewise, the 'Sun Salutation' consists of a specific sequence of yoga postures performed with synchronized breathing. This sequence consists of 10 postures set in a dynamic form, performed in a single, conscious and graceful flow (Figure 1). The postures ingeniously combine forward-bending poses countered with backward-bending ones. It is claimed that just as the rays of the sun reach every part of the globe, the sequence of these postures ensure that 'energy' reaches every part of the body. Hence, the name Sun Salutation. The sequence does not require any gadgets, takes only a few minutes to perform and can be done in a limited space. With regular practice, it is claimed that all the parts of the human body are felt to be exercised and rejuvenated (Omkar, 2007).

Studies have shown that the practice of yoga may be associated with an improvement in cardio respiratory

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Figure 1 Cycle representing the 10 postures of the Sun Salutation.

fitness (Prasad et al., 2001; Tran et al., 2001), as well as muscular strength and endurance (Birch, 1995). A study that evaluated heart rate for standing yoga postures found lower heart rates and higher rates of perceived exertion for the yoga postures, as compared to treadmill walking (DiCarlo et al., 1995). Thus, researchers have felt the need for work on fitness-related outcomes associated with yoga practice (Cowen and Adams, 2007). The amount of calories burned during a session of Sun Salutation in which the sequence of postures is repeated 120 times, classified by the weight group is given in Table 1 (Omkar, 2007).

Though research has found yoga to be equivalent to modern forms of exercise in terms of energy expenditure (DiCarlo et al., 1995; Rai et al., 1994; Raju et al., 1986), energy expenditure during the various aspects of yoga — 'asana' (the physical practice of postures), 'pranayama' (breathing exercises) and 'savasana' (relaxation), varies.Cowen and Adams (2007) in their study pointed out that a vigorous style of yoga is equivalent to modern exercises as far as heart rates are concerned but due to the varied physiological responses of the body to different styles of yoga 'asanas', different levels of physical fitness can be achieved (Cowen and Adams, 2007).

Table 1 Energy expenditure during the Sun Salutation (Omkar, 2007).

Weight (Kg)	Energy expenditure for 120 Cycles (Kcal)
55	185
65	275
77	380

The movement patterns involved in the Sun Salutation and its impact on calorie burning makes it very attractive for all practitioners (Omkar, 2007). It has also been found to decrease climacteric symptoms, perceived stress, and neuroticism in perimenopausal women, more effectively than physical exercise (Chattha et al., 2008). Experience shows that it is also an excellent warm up exercise, promoting flexibility of the spine and limbs.

Since motions at joints are all rotary, rotary moment is the product of the linear force and the moment arm or mechanical advantage of the muscle about the joint's centre of rotation. The calculation of joint forces and moments during a movement is a classical process in human movement analysis. Moments experienced by the lower extremity joints during five common yoga postures have been evaluated (Westwell et al., 2006). In this pilot study, three-dimensional motion data of joint moments obtained from a single subject were normalized to body mass (Nm/kg). Large moments generated at the hip and knee during the five postures studied were found to be comparable to those that are experienced during running. However, their study found minimal power absorption and impact forces at these joints. Thus, they concluded that yoga may be considered as a favorable alternative to running thereby minimizing joint deterioration. Hence, it is not only important but also interesting to quantify the moments and forces acting on various joints while performing the Sun Salutation. In this paper, we develop a simple mathematical model for all the postures in the Sun Salutation and compute the forces and moments occurring at various joints using the basic principles of mechanics.

Development of a mathematical model

Measurement of forces and moments can be complex and thus mathematical models are often used to estimate these loads which involve rigid body mechanics. The rigid body mechanics approach makes various assumptions about the body, including non-deformability, fixed center of mass, and homogeneity of the material.

To perform an accurate analysis we must determine information such as structural loads, geometry and support conditions. For calculation of forces and moments, the principle of superposition is considered, which states ''The moment on any bar due to the total load is the algebraic sum of the moments due to several parts of the load''. In the case of a body subjected to several loads, the principle of superposition is very helpful in calculating the moment acting at any point.

The bending moment at a section through a structural element may be defined as ''the sum of the moments about that section of all external forces acting to one side of that section''. The forces and moments on either side of the section must be equal in order to counteract each other and maintain a state of equilibrium. So the same bending moment will result from summing the moments, regardless of which side of the section is selected.

The Sun Salutation consists of ten postures. As such, the moment considered on the joints depends on the configuration of the body in each posture. Accordingly we vary the load to be considered while calculating the moments. As the body is divided into multiple segments and each segment is subjected to a different load, the bending moment at each point must be the sum of that due to each taken separately. When a joint is simply supporting the body at the ends, it plays a role of transmitting the load and no moment is generated there. But in case there is an overhang near that joint which is supporting the body, then there will be a small amount of moment due to the weight of the overhang.

An analysis of the factors that influence normal and prosthetic joint function requires an understanding of free-body diagrams. A free-body diagram can be used to schematically represent all the forces and moments acting on a joint. We have considered six different joints namely the wrist, elbow, shoulder, hip, knee and the ankle joint. For the analysis of these six joints, the body can be divided into four major segments-head, arm, trunk and legs.

The concept of equilibrium (Halliday et al., 2008) is important in understanding and determining the forces and moments occurring during specific postures of the Sun Salutation. Using the equations of plane static equilibrium, the joint reaction forces and moments can be determined for different conditions.

Table 2 Segmental relative weight and relative length of human body (Ferreira et al., 2007).

Segment	Relative weight	Relative length
Head	0.08	0.182
Arm	0.0325 × 2	0.441
Trunk	0.4074	0.288
Leg	0.2238 × 2	0.530

We need to know the body weight distribution and length distribution in order to determine the loads at each segment. This has been done with the help of the distribution chart given in Table 2 (Ferreira et al., 2007).

The following assumptions have been made while computing the joint moments:

- The body has been idealised as an arrangement of rigid links connected by the six major joints namely wrist, elbow, shoulder, hip, knee and ankle, which are considered to be hinge joints. The hip and lower back have been idealised as one joint.
- The body has been idealised as a one-dimensional system moving about the saggital plane. We have considered the saggital view because the movements during the Sun Salutation primarily take place in this plane. The results of saggital plane kinetic analysis have provided very useful profiles for examining motor patterns of normal and pathological gait (Winter and Eng, 1995).

Normalization of moments

Joint moments, commonly used to characterize gait, are affected by factors such as height and weight (Moisio et al., 2003). The un-normalized moments (expressed in Newton-meters) have significantly greater variability due to both height and weight. Normalization is done to reduce the effect of height and weight on joint moments. Two commonly used normalization methods are

- Body Mass Normalization (BMN) where joint moment is expressed in N m/kg
- Body Weight—Height Normalization (%BWHT) where joint moment is expressed as a percentage of Body Weight times Height

The percent Body Weight times Height normalization scheme is able to account for the variability of height and weight in the saggital and frontal planes (Sum et al., 1998) and hence the same has been used in the present study.

Sample calculation

To illustrate the analysis of the postures of Sun Salutation, we show a sample calculation of the moments at each of the six joints resulting from posture 8 (Figure 1). The corresponding free-body diagram considering the data from Table 2 is shown in Figure 2.

Consider the moment balance equation about the ankle joint:

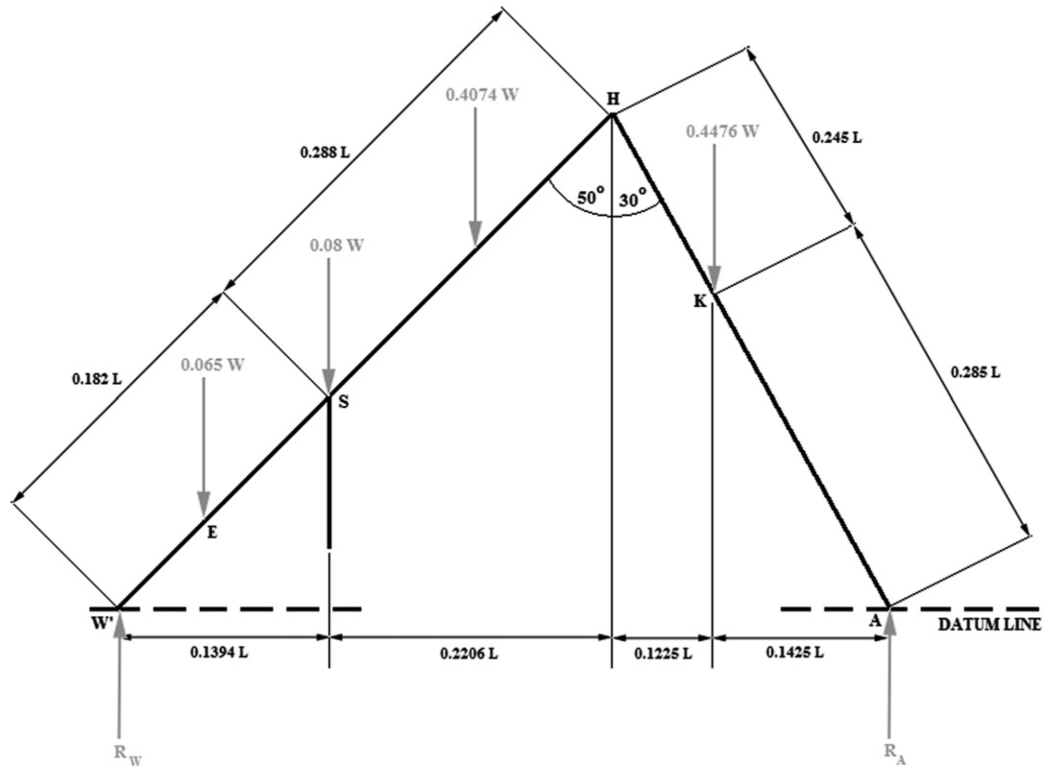

Figure 2 Schematic representation of Posture 8. Index: W′ = Wrist, E = Elbow, S = Shoulder, H = Hip, K = Knee, A = Ankle, W = Weight of Body, L = Length of Body.

$$\sum M_A = 0$$

$$(0.4476W)(0.1425.L) + (0.4074W)(0.3753L) + (0.08W)(0.4856L) + (0.065W)(0.5553L) - R_W(0.625L) = 0$$

where $\mathbf{R_W}$ (Ground Reaction Force on wrist) = 0.4666W; $\mathbf{R_A}$ (Ground Reaction Force on ankle) = 1 − R_W = 0.5334 W.

Based on the computed ground reaction forces and segmental loads of the body, we calculate the moments on the various joints, as follows:

$\mathbf{M_K}$ (Knee Moment) = R_A (0.1425 L) = (0.5334 W) (0.1425 L) = 0.076 WL
$\mathbf{M_H}$ (Hip Moment) = R_A (0.265 L) − (0.4476 W) (0.1225 L) + 0.076 WL = 0.1625 WL
$\mathbf{M_E}$ (Elbow Moment) = R_W (0.1394 L/2) = 0. 0325 WL
$\mathbf{M_S}$ (Shoulder Moment) = R_W (0.1394 L) − (0.065 W) (0.0697 L) + 0.0325 WL = 0.093 WL
$\mathbf{M_A}$ (Ankle Moment) = 0 WL
$\mathbf{M_W}$ (Wrist Moment) = 0 WL

In a similar manner, the joint moments and ground reaction forces (GRF) can be calculated for all the postures. These are shown in Table 3 and Figure 3 respectively.

Results for each posture

In posture 1, the subject is standing upright, and hence there is no moment acting on any of the joints. The foot is experiencing a reaction force due to the weight of the body. This posture reinforces the postural muscles and promotes a healthy lower back.

In posture 2, the subject is trying to bend backwards stretching the back as much as possible with the arms stretched above the head. As is evident from this posture, the hip is subjected to the maximum moment, which is in agreement with the data shown in Table 3. In order to keep the legs straight, the knee and ankle joints are simultaneously subjected to a significant amount of resisting force resulting in a moment. Also, due to an effort to stretch the arms backwards, there is a significant moment on the shoulder and the elbow. This posture provides a good stretch for the complete spinal column. This is useful for the muscles and organs of the pelvic, abdominal and chest cavities. The legs and arms are also benefited.

In postures 3 and 10, the subject bends forward and places the palms beside the feet. In this posture, the role of the arm is subdued and the majority of the load and the moment generated due to this posture are taken up by the hip, knee and the ankle. This posture promotes increased flexibility in the hamstrings and the gluteal muscles.

In posture 4, the subject takes one leg back and places the other in front. In this posture, the body tries to stretch forward on account of the hip (which is reflected by the peak hip moment in the Table 3) and legs. The leg which is placed forward experiences a significant moment at the knee and ankle. This posture promotes mobility of lower back, knee and ankle. The hip flexors and extensors are also benefitted.

The analysis of posture 4 holds true for posture 9 as well, with the difference being that the leading leg in the former

Table 3 Variation of the moments (%BWHT) on the wrist, elbow, shoulder, hip, knee and ankle joint for one cycle of the Sun Salutation.

Posture	Wrist	Elbow	Shoulder	Hip	Knee	Ankle
1	0	0	0	0	0	0
2	−0.007	−0.06	−0.077	−0.085	−0.068	−0.077
3	−0.003	−0.017	−0.012	−0.06	−0.06	−0.06
4	0	−0.042	−0.042	−0.031	−0.011	−0.016
5	−0.007	−0.007	−0.007	0.174	0.094	0
6	−0.025	−0.025	−0.007	0.095	0.072	0
7	0	−0.011	0.0085	0.066	0.172	−0.04
8	0	0.0325	0.093	0.163	0.076	0
9	−0.007	−0.007	−0.007	0.174	0.094	0
10	−0.003	−0.017	−0.012	−0.06	−0.06	−0.06
11	0	0	0	0	0	0

now makes way for the other leg and itself goes backward. We study the moments on the same leg which is now trailing and observe that there is a significant increase in the knee moment as it is subjected to the reaction force which was taken up by the ankle in posture 4.

In posture 5, the shoulder and ankle support the whole body keeping the trunk parallel to the ground. As a result the hip is subjected to a prominent moment. Although the moments on the shoulder, elbow and wrist are found to be low, they experience a high reaction force (about 62% of body weight). This posture strengthens the upper body, abdominal, and lower back muscles. It is also beneficial to the arm and feet.

In posture 6, the elbow is bent and the body is parallel to the ground. As a result there is an increase in the elbow and wrist moment with a decrease in hip and knee moments because now the majority of the ground reaction force (about 75% of body weight) is at the arm. This posture strengthens the abdomen, back, shoulders, and arms.

In posture 7, the head is raised and bent backward as much as possible, bending the spine to the maximum with the body taking the shape of an arch. The lower end of this arch is supported by the knee and ankle which are subjected to the maximum moment. Also, due to the spine stretching there is an appreciable amount of moment on the hip. This posture promotes increased lower back flexibility.

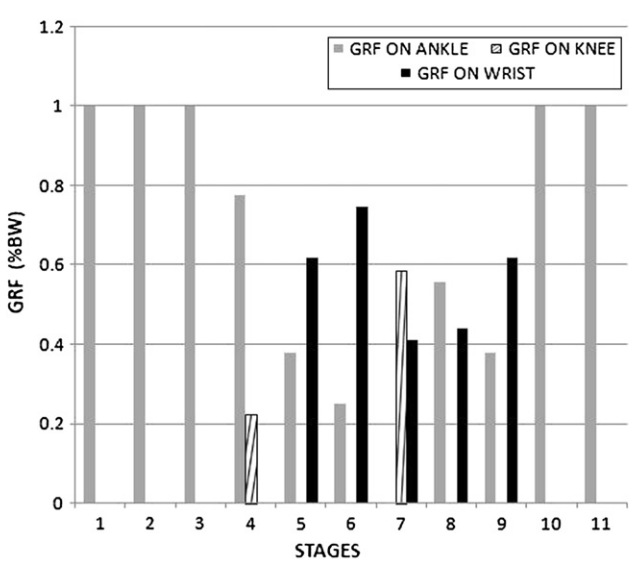

Figure 3 Variation of ground reaction force (%BW) on the ankle, knee and wrist joint while performing one cycle of the Sun Salutation. (W = Weight of Body).

In posture 8, the hips are moved as high as possible and the spine is stretched downward taking the head as close to the ground as possible. Due to this, the hip is subjected to high moment. In this posture, an effort is made to keep the arms straight and fixed, which results in a greater resisting force developed in the arms which is translated into a high shoulder moment as shown in Table 3. The ground reaction force is shared between the wrist and the ankle, with the ankle taking a slightly more load. This posture stretches the hamstrings, increases upper body strength and promotes increased flexibility to the chest and mid back.

Discussion

Figure 4 shows a very interesting pattern in the variation of moments for the joints of the upper body. It reflects that the elbow and shoulder joint moments vary almost in a similar manner. Since the arms are being extended beyond the shoulder in the second and third posture, the shoulder experiences a slightly greater moment than the elbow, hence it is subjected to a greater resisting force. In the sixth posture, the elbow joint shows a higher value of moment compared to the other stages as it is in flexion and at the same time experiences a ground reaction force with the hand in contact with the ground, supporting the body. The eighth posture shows a significant difference in the moments of the elbow and the shoulder joint. With a high moment being generated, the shoulder joint plays a key role in this posture. This is because an effort is made to keep the arms straight and fixed while the hip joint is lifted up. In all other stages the moments on the elbow and the shoulder joints are nearly equal.

Meanwhile, there is almost negligible moment on the wrist for the entire cycle except for the sixth posture. In the second and third posture, the palm is just resting on the ground without supporting any load, hence it accounts for the moment only due to the weight of the arm which is negligible in comparison to the moments on the other joints.

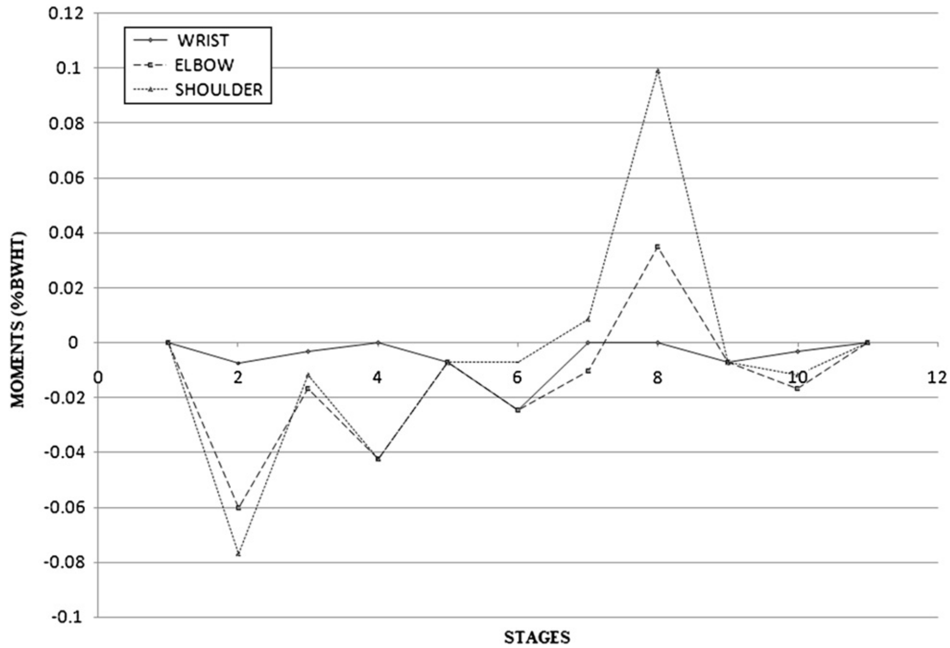

Figure 4 Variation of moments on the wrist, elbow and shoulder joint during one cycle of the Sun Salutation.

The posture in which the wrist acts as a simple support, the wrist plays the role of transmitting the load. Hence the wrist experiences a moment only due to overhang, if any.

Similarly, Figure 5 shows the pattern of variation of moments for the joints of the lower body. The hip and knee joint moments show almost a similar pattern of variation during the cycle of Sun Salutation. The hip joint shows a greater value of moment in all the postures except in the seventh posture where the knee joint supports the body. The hip is the major joint which is subjected to peak moments during the Sun Salutation. The moment on the ankle doesn't show any characteristic curve due to its variable role in transmitting reaction forces in certain postures while transmitting moments in others.

Studies have shown that dynamic moments with high magnitudes and rates, applied with unusual distribution patterns, are optimal for osteogenesis, and that these strain-loading histories play an important role in determining bone morphology (Wang et al., 2006). Persistent, low-amplitude, high-frequency mechanical strains have also been found capable of increasing bone formation rates (Fritton et al., 2000). During the Sun Salutation the joints are subjected to dynamic strains and moments as the body executes different postures during the cycle.

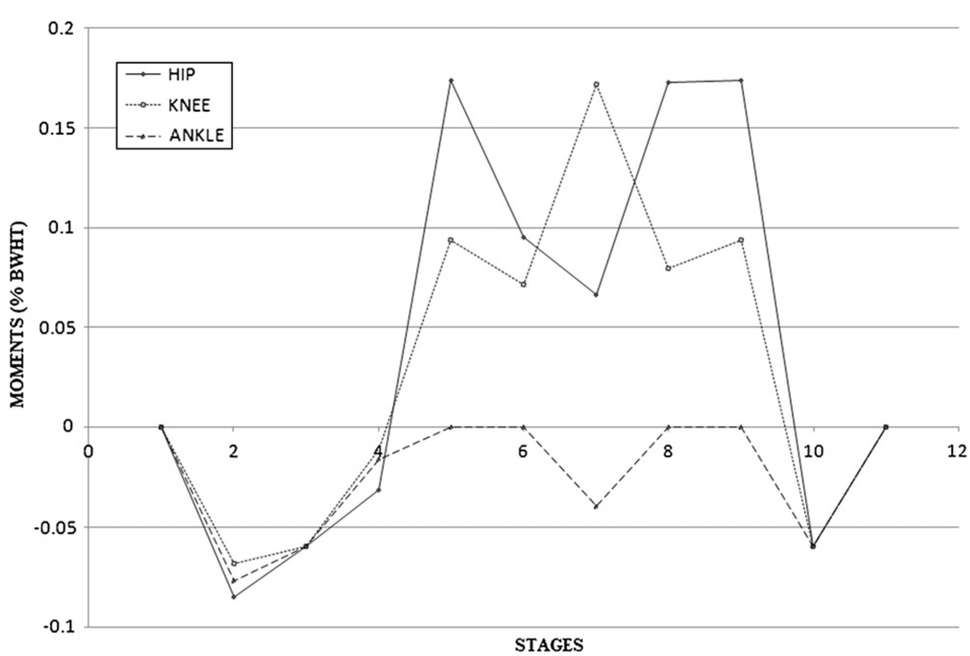

Figure 5 Variation of moments on the hip, knee and ankle joint during one cycle of the Sun Salutation.

Table 4 Comparison of moments during the sun salutation with average moments during daily activities (Chou et al., 2005; Finley et al., 2001; Simoneau et al., 2000; Westwell et al., 2006) and peak moments which joints sustain during daily activities (Escamilla et al., 2001; Holzbaur et al., 2007).

Joint	Moments (%BWHT)			
	Average during daily activities	Average during the Sun Salutation	Peak during the Sun Salutation	Peak values during daily activities
Ankle	0.08	0.023	0.077	0.13
Knee	0.09	0.064	0.172	0.496
Hip	0.098	0.083	0.174	0.416
Shoulder	0.08	0.024	0.093	0.097
Elbow	0.012	0.02	0.06	0.07
Wrist	0.013	0.004	0.025	0.031

The moments which the joints are subjected to during the Sun Salutation are comparable to that of daily living activities and exercises as shown in Table 4 — **Average during Daily Activities** (Chou et al., 2005, Finley et al., 2001, Simoneau et al., 2000, Westwell et al., 2006). However, the power absorption and impact forces experienced during yoga are minimal since the poses are held in a static position whereas daily living activities and exercises involve higher power absorption and impact forces during loading response (Westwell et al., 2006). As seen from Table 4 — **Peak Value during Daily Activities** (Escamilla et al., 2001, Holzbaur et al., 2007), the joints are subjected to submaximal loadings during the Sun Salutation thus ensuring that none of the joints are overstressed.

Conclusions

A mathematical model for each of the postures in the Sun Salutation is developed based on rigid body mechanics and free-body diagrams. The forces and moments encountered by various joints are computed based on the concept of static equilibrium. A number of assumptions have been made in the development of the model described in this paper. However, the fact that the ankle and wrist, when modeled, are found to play a primary role in transmitting the ground reaction forces during the Sun Salutation, while the hips bear the highest joint moment, mirrors what is found in practice. As such it would suggest the model to be a useful tool for predicting the forces and moments that occur not only during the Sun Salutation but for other yoga postures too, as well as in predicting the benefits of yoga in general.

Certainly, the present data would suggest that an important benefit of the Sun Salutation postures are that the joints involved are subjected to submaximal loadings as compared to more high impact exercises for which the energy expenditure is comparable. Practicing the Sun Salutation postures regularly, therefore, by producing high joint moments yet submaximal joint loading, would suggest they could have a beneficial role to play in bone remodelling and osteogenesis.

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