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Ground Reaction Forces Generated by Twenty-eight Common Hatha Yoga Postures

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Ground Reaction Forces Generated
By Twenty-eight Common
Hatha Yoga Postures

Sylvia Wilcox

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

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Yoga adherents claim many benefits of the practice, including promotion of bone health and prevention of osteoporosis. However, few, if any, studies have investigated whether yoga enhances bone mineral density. Furthermore, none have identified force generation in yoga. The purpose of this study is to collect ground reaction force (GRF) data on a variety of common hatha yoga postures that would be practiced in fitness centers or private studios.

Twelve female and eight male volunteers performed a sequence of 28 common hatha yoga postures while ground reaction force data were collected with an AMTI strain-gauge force plate. The sequence was repeated six times. Four variables were studied: the maximum vertical GRF, the mean vertical GRF, the maximum resultant GRF, and the mean resultant GRF.

Univariate analysis was used to identify mean values and standard deviations for each of the four variables. Multivariate analysis revealed some variation due to gender but none due to age or weight. Means were similar across all poses and subjects, and standard deviations were small.

This unique yoga sequence produced low impact forces in both upper and lower extremities. Further research is warranted to determine whether these forces are sufficient to promote osteogenesis or maintain current bone health in yoga practitioners.

Key words: yoga, ground reaction force, low-impact, weight-bearing

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Ground Reaction Forces Generated
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Hatha Yoga Postures

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Abstract

Yoga adherents claim many benefits of the practice, including promotion of bone health and prevention of osteoporosis. However, few, if any, studies have investigated whether yoga enhances bone mineral density. Furthermore, none have identified force generation in yoga. The purpose of this study is to collect ground reaction force (GRF) data on a variety of common hatha yoga postures that would be practiced in fitness centers or private studios.

Twelve female and eight male volunteers performed a sequence of 28 common hatha yoga postures while ground reaction force data were collected with an AMTI strain-gauge force plate. The sequence was repeated six times. Four variables were studied: the maximum vertical GRF, the mean vertical GRF, the maximum resultant GRF, and the mean resultant GRF.

Univariate analysis was used to identify mean values and standard deviations for each of the four variables. Multivariate analysis revealed some variation due to gender but none due to age or weight. Means were similar across all poses and subjects, and standard deviations were small.

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Key words: yoga, ground reaction force, low-impact, weight-bearing

Introduction

Yoga is a popular form of exercise practiced in private studios, fitness clubs, homes, and recreation centers across the nation. The most commonly practiced form of yoga is hatha yoga, which combines three key features: the postures (asanas), the mind, and the breath.[1]

Yoga practitioners (yogis) claim that yoga reduces stress[2] and relieves headaches.[3] Yoga may also reduce pain and disability in osteoarthritis of the knee,[4] increase strength and flexibility,[5] and effectively treat some symptoms of carpal tunnel syndrome.[6] Some assert that practicing yoga promotes healthy bones and prevents osteoporosis.[7,8] This assertion is intuitive due to the fact that many of the asanas practiced in yoga are weight-bearing.

Researchers believe that exercise exerts its effects on the bones by both the force of gravity and the force of muscle contractions.[9] A wide variety of exercise interventions appear to corroborate this opinion. Weight training regimens using variable resistance machines improved bone mineral density (BMD) at numerous skeletal sites including the femoral neck and lumbar spine in both young adult and elderly men and women.[10,11] High-impact aerobic exercise increased proximal femur BMD in men and women 50 to 73 years of age[12] and improved BMD at numerous sites, such as the spine and femur, in premenopausal women.[13] An exercise trial that compared low- and moderate-impact exercises such as walking, stair climbing, and light jogging with weight lifting and rowing produced significant increases in BMD of the whole body, proximal femur, and lumbar spine which were similar for both groups of postmenopausal women.[14] Low-impact weight-bearing exercises combined with a weight- lifting program maintained BMD of the spine and hip in postmenopausal women,[15] and low-impact walking at a speed > 6.14 km/h improved BMD of the legs and total body (although not significantly) in postmenopausal women.[16] Finally, a year-long intervention comparing low-impact and high-impact exercise programs showed that BMD of the lumbar spine was maintained in both groups of early postmenopausal women.[17] This study was one of only a few that included ground reaction force (GRF) measurements normalized to body weight in their study designs and thus identified possible intensities of exercise that may benefit bone health (see Table I).[17, 18, 19] Specifically, Grove and Londeree[17] used exercises that produced GRF greater than or equal to two times the body weight for their high-impact group and exercises that generated a GRF less than or equal to 1.5 times the body weight for the low-impact group.

Table II reports results from additional studies that identify either a range of or average peak GRF measured in a variety of exercises normalized to subjects' body weights. These include peak forces measured for barefoot subjects who performed intermittent and continuous jumps.[20] In addition, Johnson *et al.*[21] identified GRF of 1.13 times body weight, 1.74 times body weight, and 1.27 times body weight for walking, low-impact marching, and pushing off the aerobic step, respectively. Rousanoglou and Boudolos[22] quantified GRF of various exercises using both male and female aerobics instructors. Although the aforementioned studies were not designed to measure the effect of exercise on BMD, the data are useful in categorizing different types of exercise as high- or low-impact and in providing a reference for comparison to the GRF generated by hatha yoga asanas.

Hatha yoga poses that are weight-bearing include those that are supported by one to four extremities at a time. Although the typical yoga session involves little or no jumping, muscles and joints are loaded using body weight, gravity, and varying amounts of time in sustained holds, thus employing concentric, eccentric, and isometric contractions. Furthermore, force is generated as participants accelerate into and out of the postures, change their center of mass, and transfer weight between one or more extremities at a time. The forces generated by these movements may be similar to those measured in low-impact exercises, strength-training programs, and walking regimens, all of which have resulted in beneficial effects on bone mineral density. To the researcher's knowledge, the effect of yoga's weight-bearing postures on bone health has not been examined, nor have studies illustrating yoga's force generating qualities been conducted. Therefore, the primary objective of this study is to collect data on ground reaction forces generated by common hatha yoga postures and compare the results to other forms of exercise that are shown in the literature to benefit bone health.

Methods

Subjects

Male and female yoga instructors and intermediate-level yoga practitioners were recruited from local private studios and fitness centers through posted advertising, phone calls, and personal contact. These individuals possessed the expertise and stamina required to execute the sequence of asanas six times during the data-collection session. Twelve women ages 22 to 49 (mean: 28.3 years) and eight men 24 to 55 (mean age: 34.4 years) volunteered to participate. Weight and height ranges for women were 48.4 to 88.1 kg and 152.4 to 177.2 cm (mean: 61.2 kg; 167.3 cm). Ranges for men were 68.9 to 86.5 kg and 170.2 to 186 cm (mean:77.1 kg; 178.2cm). One male and eight female subjects were yoga instructors.

Equipment

A single researcher used a 40x60 cm AMTI (Watertown, MA, USA) force plate to measure GRF at 1000 Hz. The data files were exported into Matlab (MathWorks, Natick, MA, USA) in order to calculate mean and average vertical and resultant GRF.

Data analysis

Data were analyzed using Microsoft Office Excel 2007 and SPSS Statistics 17.0 software (SPSS Inc. Chicago, IL). Mean values and standard deviations for all four variables on each posture were calculated across all subjects. Multivariate analysis checked for variations due to gender, weight, and age.

Variables

The independent variable—the yoga sequence—was the same for all subjects and was executed under two different conditions, as described below. Four dependent variables were measured for each condition: the peak vertical GRF, average vertical GRF, peak resultant GRF, and average resultant GRF. All GRF values were normalized to body weight. The researcher expected that the data would produce a similar range of GRF for all subjects. This assumption was based upon the experience of McNair and Prapavessis,[23] whose study of adolescent boys and girls jumping from a height of 0.3 meters onto a force plate produced no significant differences in the GRF measured between the genders.

Procedure

The study was approved by the Brigham Young University Institutional Review Board. Subjects were educated over the phone or in person about the study and given information prior to the session to review on their own time. Subjects reported to the Biomechanics Lab at BYU and signed a consent form prior to data collection. Body mass in kilograms and height in centimeters were measured using an electronic scale and stadiometer, respectively. Subjects then participated in a practice session and warm up. All subjects executed the same yoga sequence, which consisted of 28 hatha yoga postures typically incorporated into beginning or intermediate-level yoga classes (see Table III). The perimeter of the force plate was marked on a sticky yoga mat, which was then positioned over the force plate, to keep participants' hands and feet oriented to the plate area. Condition one included the first three sessions, in which the subject began the sequence by standing over the force plate and variables were measured at either the lower extremities (or extremity) or the upper extremities (or extremity), depending upon which posture was being performed. Condition two comprised the last three sessions, wherein the subject began the sequence by standing on the mat in front of the plate and stepping back with either one or both lower extremities (see Figures 1 and 2). Each posture was performed within a five-second interval. Preliminary testing of timed intervals ranging from three to seven seconds proved that the five-second interval was optimum for complete execution of each asana. The researcher verbally cued the subject on when to begin the sequence and when to begin executing each successive posture and simultaneously started the Vicon Nexus program, which stopped recording automatically after five seconds.

Results

Descriptive statistics are found in Table IV, which displays the asanas in order of execution and identifies the mean forces generated across all subjects at the specific limb or limbs. Figures 3a through 31b illustrate and further describe each posture. Maximum vertical GRF and maximum resultant GRF are identical or almost identical for condition 1, wherein the subject began the sequence standing over the force plate. Likewise, mean vertical GRF and mean resultant GRF are almost identical for all postures in condition 1. In condition 2, more variation is apparent between the maximum vertical and resultant GRF, as well as the mean vertical and resultant GRF. The slightly larger differences between vertical and resultant forces in this condition can possibly be explained by variations in the speed at which the subject placed his or her foot on the mat as in, for example, each of the virabhadrasana (warrior) poses; whether the subject needed to adjust his or her balance on one or both feet once landed on the mat; how much force the participant generated with the forward versus the rear leg on postures such as trikonasana (triangle), and parsvakonasana (side angle); or how steady the balance on the arm or feet was while executing vasisthasana (side plank).

Comparison of Tables II and IV identify this yoga sequence as low-impact since the results for all measured variables are less than two times body weight. The GRF for the yoga postures is also lower than the values obtained from the various low impact activities listed in Table II with one exception. The highest maximum vertical and resultant values in the present study (1.47 ± .24; 1.49 ±.25) were from the two-footed landing as participants leaped from dandasana (plank) to uttanasana (forward fold). The generated force is similar to that measured for low-impact exercises and walking[19] and for walking and stepping down or pushing off an 8-

inch bench.[21] The lowest maximum vertical and resultant values (.27 ±.03; .29 ±.05) were measured from the feet in condition 2 for urdva mukha svanasana (upward facing dog), wherein the bulk of body weight is absorbed through the arms while the large muscles of the lower back, buttocks, and thighs contract to keep the legs off the floor.

Multivariate analysis revealed no significant differences due to weight or age. Although mean ranges and standard deviations were small across all subjects and postures, significant variations in five of the postures displayed in Table V were due to gender, contrary to the researcher's expectation.

The differences in the first four of these postures—urdva mukha svanasana; dandasana; pincha mayurasana (dolphin); and adho mukha svanasana (downward facing dog)—may be explained by the difference in mass distribution between males and females. Body mass in men is concentrated in the upper body, whereas center of mass in women is below the waist. In all four of these postures, the force through the arms is greater for men than women; conversely the force through the feet is greater for women than for men on all four of the postures.

The difference in most of the variables for virabhadrasana (crescent) may be explained by the researcher's observations of males and females as they executed the posture. Virabhadrasana is preceded by adho mukha svanasana and requires that one leg be brought forward and placed between the hands, after which the arms are raised overhead while the subject balances on the ball of the back foot and assumes a lunge with the forward leg. All vertical and resultant forces in the forward leg are greater for males than females, while mean vertical and resultant forces are smaller in the rear leg for males than for females. The rear leg adjustments are fairly minor since the subject is already on the balls of the feet in the preceding pose. The researcher observed that some of the males used momentum to swing the back leg forward into the lunge, landing with greater force, in contrast to the slower transition demonstrated by most of the female participants. This variation in execution could result from differences in lower extremity length and hip flexor flexibility between male and female participants as well as experience using abdominal contractions and exhalation to facilitate steady movement of the rear leg forward rather than using momentum to swing it forward.

Discussion

The main purpose of this study was to obtain GRF from typical hatha yoga postures and determine if these forces are comparable to other forms of exercise that are shown in the literature to benefit bone health. The mean values clearly demonstrate that this particular study design produced low-impact forces which are less than those measured in previously cited trials. The difference is that all of these reported only the vertical component of the GRF which seems to be the measurement of most interest since it measures impact through the lower extremities. In contrast, execution of the yoga postures produced values for both upper and lower extremities as well as resultant GRF measurements which captured the vertical, antero-posterior and medio-lateral (shear) components of movement. What these unique forces could mean for bone health or osteoporosis prevention is an area ripe for further analysis.

As previously pointed out in this paper, very few trials describe exercise regimens with GRF data. However, a vast number of studies conducted in recent decades focus on various types of exercise programs or activities that are most likely to benefit bone health in children, adolescents, and adults of all ages. The intent is to identify interventions that best promote bone mineral accrual, maintain BMD in women and men as they age, or at least slow the rate of bone mineral loss, and thereby decrease the morbidity associated with falls and fractures. Results of these studies are mixed, with no consensus on either the best type of exercise or the appropriate intensity or frequency to achieve beneficial results.

The lack of consensus may be explained by the many complex mechanisms that influence bone growth and strength. Researchers observe that bone responds best to exercise during growth since it appears that proportionally more osteoblasts are present on bone surfaces during childhood and adolescence than in adulthood.[24] Growth on the periosteum (outer surface) of the bone gained during childhood not only improves overall bone strength, but apparently is not lost (resorbed) in adulthood.[24] For this reason, many researchers study ways in which to optimize bone mineral accrual through programs for children that incorporate jumping exercises into regular physical education classes.[25, 26]

Dynamic loading (concentric contraction) is more osteogenic than static loading (isometric contraction) because it creates pressure gradients within the cellular matrix of the bones.[24] Since bone cells are so sensitive to shear stress produced by the flow of viscous fluids near them, complex processes are initiated that result in bone growth (osteogenesis). With higher levels of strain, as in high impact exercises that deform the bones (cause bending or compression), the fluid flow within the canal-like system of bone cells is stimulated. High impact exercise trials incorporating running and jumping, and cross sectional analyses comparing high impact sports like squash or basketball to lower impact sports such as swimming or aerobic dancing support these observations, since athletes who participate in high impact activities tend to have higher bone mineral density that athletes in low impact sports. [27, 28, 29]

However, bone cells also reach a level of saturation to these high strains, meaning that the cellular response diminishes with repetitive high strain, presumably because the fluid flow is dampened when the same stimulus is applied repeatedly.[30] Srinivasan et al.[31] examined this phenomenon in an animal study using turkeys and mice. In the turkey experiment, low-magnitude loading with rest cycles compared to low-magnitude loading alone significantly increased the area of mineralization on the periosteum. In mice, three conditions were examined: low-magnitude loading alone, low-magnitude loading with rest, and high-magnitude loading. Both the high-magnitude and low-magnitude with rest regimens produced similar results in the measured bone formation parameters such as bone formation rate, osteoblast activity on the periosteum, and cross sectional area. This animal model could partially explain why weight lifting, resistance training, and low-impact exercise programs, as well as high-impact exercises appear to strengthen bones.[32] If these findings apply to humans, then the implication for low-impact modes of exercise such as yoga, which insert rest intervals between the applied loads, is that the force could be sufficient to stimulate bone cells in individuals who, because of age, injury, or disability, are not able to participate in high-impact activities.

Researchers also acknowledge that the standard method of assessing bone density, dual energy x-ray absorptiometry (DEXA), does not always adequately portray true bone health.[33] Low BMD does not necessarily mean that bones are weak and prone to fracture, nor does normal or high BMD always imply that bones are strong and healthy. Application of a force or strain on a bone results in mineral accrual at that site and may alter both its shape and strength. These changes may be undetected by DEXA. A study by Turner and Robling[33] demonstrated this in rat ulnas. Cross-sectional examination of the loaded ulnas showed that new bone was formed where it was most needed—the site where mechanical strain was applied—which altered the shape and strength of the bones. The very small change noted in BMD of the rat ulnas by DEXA did not accurately reflect the large increase that they measured in the amount of force the ulnas could sustain before failing.

In summary, the previous discussion suggests that much remains to be learned about how bones react and grow in response to external stimuli and what other features of its structure besides bone density could be indicators of bone health. Similarly, as newer methods of assessing bone health are refined, new light may be shed on the mechanisms by which so many varieties of exercise exert their beneficial effects on the skeleton. In the meantime, whether a comparison of yoga athletes with athletes of other disciplines, using the standard DEXA measurement, would provide evidence to the scientific community that yoga may promote bone health and prevent osteoporosis could be studied further.

One of the strengths of the present study is that it provides new GRF data on hatha yoga poses and identifies those used in this design as low-impact. Another strength is that the volunteer sample size was large enough to reduce chance variations in the results. Indeed, the sequence demonstrated very little variation between subjects in spite of certain differences in performance due to skill, strength, and flexibility. The sample also represented a wide range of men and women who practice yoga. The five-second interval allowed subjects sufficient time to execute each pose, with only a few exceptions when an individual's balance faltered. In addition, the study is applicable to the real world since the individual postures in the design are common to most types of beginner to intermediate-level hatha yoga classes and represent a variety of impacts to all of the extremities. For instance, the first 10 poses make up the Surya namaskara A (sun salutation), a sequence which is typically repeated numerous times in yoga classes and in one or more iterations.

This study is also rather unique because it quantifies impacts sustained by the upper extremities. Apparently very little is written about low-impacts generated through the upper extremities and their influence on the skeleton. Moderate to high reaction forces ($\geq 1.6 \leq 3.0$ x BW) have been quantified for gymnasts performing the floor exercise round-off and Yurchenko vault round-off, respectively.[34] Mean reaction force for the pommel horse measured 1.5 x BW, with forward and back handsprings averaging 2.9 and 3.6 x BW, respectively, in another study of male gymnasts.[35] These high forces may not be well tolerated by the upper body and are likely the reason why gymnastics is such a high-risk sport for injury. On the other hand, weight bearing by the upper extremities in the present study ranged from 0.63 to 1.08 x BW. Whether this force magnitude is osteogenic remains to be explored, with the following exception.

Researchers designed a unique intervention by vertically aligning a force platform on a wall so that healthy females aged 25 to 45 years, who faced it with one arm extended at shoulder level, could impact the wall.[36] With wrists extended, the subject stood 40 cm from wrist joint to wall and then fell forward against the plate. Once trained in the procedure, subjects were randomly assigned to carry out the exercise either on a firm or padded wall in their homes. Subjects performed this exercise 36 times per day, 3 days per week for 6 months. The impact load, or peak perpendicular reaction force, loading rate, and impulse were measured as were pre- and post-intervention BMD measurements of the distal and ultradistal radius and total radius.

The mean impact load or reaction force ranged from 46.9% ± 33.6% of BW in subjects who impacted a firm wall. Changes in bone mineral content (BMC) at the distal radius and total radius, and changes in bone area of the ultradistal radius and total radius were significantly greater in this group than in the group that impacted the padded wall. The researchers concluded that the impact load, or force, independently predicted the before and after changes at the distal radius and total radius. Maximum GRF measured at the upper extremities in the present study were similar to the impacts mentioned above and ranged from 0.63 to 1.08 times BW (see Table IV). Designing a 3 day per week, 6 month yoga intervention with at least 36 impacts to the upper extremities in each session is certainly feasible. Thus, it may be possible to show that hatha yoga exercises could similarly influence BMC.

Some of the study’s limitations warrant mentioning. Not all yoga sequences are performed at the tempo used in this design. Further accelerating the speed of execution could result in higher GRF since force equals mass times acceleration. Additionally, the results cannot be generalized to more vigorous styles of yoga which require a higher level of strength and expertise than was required in this design. Finally, since the study only concerns GRF measurement, no inference or conclusions can be drawn about the effects the impacts could have on specific muscles and joints.

Conclusion

In conclusion, it is evident from a plethora of research on exercise and bone density that many kinds of weight-bearing activities, both high- and low-impact, are beneficial to individuals of all ages. Since yoga is weight-bearing, using the body as resistance, it may positively influence bone health as many of its adherents believe. Thus, it may provide an acceptable alternative to those who choose not to participate in high-impact sports or exercises. Additionally, the GRF generated in the upper extremities may indeed be sufficient to promote or maintain BMD and is worthy of further analysis. Finally, animal models illustrating the apparent benefit of rest intervals and low-magnitude forces on the bones could apply to yoga since pauses are often inserted between postures. Such low-magnitude forces with rest intervals between the applied loads, could be sufficient to stimulate bone cells in individuals who decline or are not able to participate in high-impact activities. Research in any of the above areas would promote clearer understanding of yoga's influence on bone health.

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Table I.—Summary of studies by exercise type and intensity and influence on bone mineral density (BMD) expressed as a ratio to body weight (BW).

Author & Year	Population	Study duration	Exercise type	Ground reaction force	Results
Grove & Londeree, 1992	early post menopausal women	1yr	High impact vs low impact	≥2xBW ≤1.5xBW	Both groups maintained BMD lumbar spine L2-L4
Bassey & Ramsdale, 1995	postmenopausal women	1yr	Heel drops vs low impact/ flexibility	2.5-3.0xBW	No change in BMD for either group at femur or spine
Heinonen et al., 1996	pre-menopausal women	18mo	High impact step & aerobics vs control	2.1-5.6xBW	Significant increase in BMD at femoral neck for impact group
Kohrt et al., 1997	postmenopausal women	11mo	Ground reaction (stairs, jogging) vs joint reaction (weights, rowing)		Both groups increased BMD of whole body, lumbar spine, and proximal femur
Bassey et al., 1998	pre- and post-menopausal women	18mo	Vertical jump from 8.5cm 6days/week	3.0-4.0xBW	Only premenopausal women had significant increase in BMD of proximal femur
Borer et al., 2007	postmenopausal women	15wks	Walking, variable speed & intensity	1.22xBW	Leg & total body BMD preserved at speeds>6.14km/hr

Table II. — Mean ground reaction force (GRF) by exercise type expressed in relation to body weight (BW).

Author and year	Exercise	GRF/BW
Grove & Londeree 1992[19]	Jumping jacks	3.29
	Running in place	2.47
	Knee to elbow with jump	2.79
	Slow walk	1.19
	Fast walk	1.49
	Heel jack without jump	1.34
	Charleston	1.32
Johnson *et al.*, 1992[21]	Walking	1.13
	Slow jog	2.26
	Low impact marching	1.74
	High impact double-hop knee lift	3.14
	Step push-off	1.27
	Step down	1.51
Kato & Bassey, 2002[20]	Two-footed jump, intermittent	4.22 ± 0.24
	Two-footed jump, continuous	4.08 ± 0.17
	Heel drops	3.38 ± 0.17
Rousanaglou & Boudolos, 2005[22]	Step touch	2.0
	Leap with triple step	2.75

Table III. — Sequence of 28 hatha yoga postures.

Name in Sanskrit (English)
1. Tadasana (mountain)
2. Uttanasana (forward fold)
3. Urdva mukha uttanasana (monkey)
4. Dandasana (plank)
5. Chaturanga dandasana (crocodile)
6. Urdva mukha svanasana (updog)
7. Adho mukha svanasana (downward facing dog)
8. Uttanasana (forward fold)*
9. Tadasana (mountain)*
10. Utkatasana (chair)
11. Parivrtta utkatasana (twisting chair)
12. Ardha uttanasana (airplane)
13. Virabhadrasana 1 (warrior)
14. Virabhadrasana 3 (warrior)
15. Virabhadrasana 2 (warrior)
16. Trikonasana (triangle)
17. Virabhadrasana (variation; reverse)
18. Utthita parsva konasana (side angle)
19. Baddha parsva konasana (bound side angle)
20. Dandasana (plank)*
21. Vasisthasana (side plank)
22. Vasisthasana (side plank on one leg)
23. Pincha mayurasana (scorpion prep/dolphin)
24. Adho mukha svanasana (downward facing dog)*
25. Virabhadrasana (variation; crescent)
26. Parivrtta parsva konasana (twisting angle/twisting warrior)
27. Parsvottanasana (pyramid)
28. Ardha chandrasana (half moon)
29. Vrksasana (tree)
30. Utthita hasta padangusthasana (standing big toe)
31. Garudasana (eagle)
32. Bakasana (crow)

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*Postures repeated for smooth execution of the sequence.

Table IV.—Mean (SD) vertical and resultant ground reaction force (GRF) values each posture across all subjects, expressed as a ratio to body weight.

Hatha yoga posture	Limb(s) measured	Maximum vertical grf	Mean vertical grf	Maximum resultant grf	Mean resultant grf
Tadasana (mountain)	Legs	1.04 (.02)	0.99 (.00)	1.04 (.02)	0.99 (.02)
Uttanasana (forward fold)	Legs	1.05 (.02)	0.99 (.00)	1.06 (.02)	0.99 (.00)
Urdva mukha uttanasana (monkey)	Legs	1.03 (.03)	0.99 (.00)	1.00 (.07)	0.99 (.00)
Dandasana (plank)	Arms	1.08 (.11)	0.76 (.03)	1.10 (.09)	0.77 (.03)
	Legs	0.50 (.11)	0.23 (.05)	0.56 (.13)	0.25 (.05)
Chaturanga dandasana (crocodile)	Arms	0.82 (.04)	0.75 (.03)	0.83 (.03)	0.76 (.02)
	Legs	0.33 (.04)	0.24 (.03)	0.36 (.05)	0.27 (.04)
Urdva mukha svanasana (upward facing dog)	Arms	0.82 (.04)	0.75 (.03)	0.83 (.03)	0.76 (.02)
	Legs	0.27 (.03)	0.21 (.03)	0.29 (.05)	0.22 (.03)
Adho mukha svanasana (downward facing dog)	Arms	0.84 (.06)	0.50 (.02)	0.85 (.05)	0.54 (.02)
	Legs	0.64 (.04)	0.48 (.03)	0.71 (.05)	0.53 (.03)
Uttanasana (forward fold)	Legs takeoff	0.98 (.30)	0.18 (.03)	1.15 (.37)	0.20 (.04)
	Legs landing	1.47 (.24)	0.80 (.06)	1.49 (.25)	0.81 (.06)
Tadasana (mountain)	Legs	1.10 (.04)	0.99 (.00)	1.10 (.04)	0.99 (.00)
Utkatasana (chair)	Legs	1.06 (.02)	0.99 (.00)	1.07 (.02)	0.99 (.00)
Parivrtta utkatasana (twisting chair)	Legs	1.04 (.01)	0.99 (.00)	1.05 (.05)	0.99 (.00)

Table IV.—continued

Hatha yoga posture	Limb(s) measured	Maximum vertical grf	Mean vertical grf	Maximum resultant grf	Mean resultant grf
Ardha uttanasana (half forward fold/airplane)	Legs	1.04 (.03)	0.99 (.00)	1.04 (.03)	0.99 (.00)
Virabhadrasana 1 (warrior)	Forward leg	1.07 (.02)	0.68 (.04)	1.07 (.02)	0.70 (.04)
	Rear leg	0.75 (.19)	0.35 (.04)	0.86 (.17)	0.38 (.04)
Virabhadrasana 3	Balancing leg	1.04 (.02)	0.87 (.04)	1.05 (.02)	0.87 (.03)
Virabhadrasana 2 (warrior)	Forward leg	1.03 (.05)	0.65 (.03)	1.03 (.05)	0.66 (.03)
	Rear leg	0.75 (.15)	0.36 (.03)	0.83 (.16)	0.39 (.04)
Trikonasana (triangle)	Forward leg	0.67 (.06)	0.57 (.02)	0.70 (.06)	0.59 (.02)
	Rear leg	0.56 (.06)	0.43 (.02)	0.61 (.06)	0.47 (.03)
Virabhadrasana (reverse)	Forward leg	0.66 (.04)	0.52 (.04)	0.68 (.04)	0.54 (.04)
	Rear leg	0.55 (.05)	0.47 (.04)	0.59 (.05)	0.51 (.04)
Utthita parsvakonasana (side angle)	Forward leg	0.71 (.03)	0.61 (.03)	0.72 (.03)	0.63 (.03)
	Rear leg	0.55 (.05)	0.38 (.03)	0.60 (.04)	0.41 (.03)
Baddha parsvakonasana (bound side angle)	Forward leg	0.74 (.05)	0.66 (.03)	0.75 (.04)	0.66 (.07)
	Rear leg	0.40 (.03)	0.34 (.03)	0.45 (.03)	0.38 (.04)
Dandasana (plank)	Arms	0.90 (.11)	0.67 (.02)	0.93 (.11)	0.71 (.02)
	Legs	0.48 (.07)	0.33 (.02)	0.53 (.08)	0.36 (.03)
Vasisthasana (side plank)	Arm	0.70 (.07)	0.66 (.10)	0.70 (.06)	0.64 (.02)
	Legs	0.45 (.05)	0.36 (.02)	0.49 (.07)	0.37 (.03)
Vasisthasana (upper leg lifted)	Arm	0.67 (.03)	0.62 (.03)	0.67 (.02)	0.63 (.02)
	Leg	0.40 (.03)	0.36 (.03)	0.42 (.04)	0.38 (.04)

Table IV.—continued

Hatha yoga posture	Limb(s) measured	Maximum vertical grf	Mean vertical grf	Maximum resultant grf	Mean resultant grf
Pincha mayurasana prep (dolphin)	Arms	0.71 (.04)	0.57 (.05)	0.72 (.05)	0.59 (.40)
	Legs	0.55 (.06)	0.42 (.04)	0.61 (.07)	0.45 (.05)
Adho mukha svanasana (downward facing dog)	Arms	0.63 (.07)	0.46 (.04)	0.67 (.06)	0.51 (.04)
	Legs	0.62 (.05)	0.53 (.06)	0.67 (.04)	0.57 (.06)
Virabhadrasana (crescent)	Forward leg	0.97 (.10)	0.60 (.03)	0.99 (.10)	0.62 (.03)
	Rear leg	0.63 (.06)	0.39 (.03)	0.70 (.07)	0.42 (.04)
Parivrtta parsvakonasana (twisting angle/warrior)	Forward leg	0.76 (.05)	0.67 (.04)	0.78 (.05)	0.69 (.03)
	Rear leg	0.43 (.05)	0.32 (.04)	0.47 (.06)	0.34 (.05)
Parsvottanasana (pyramid)	Forward leg	0.91 (.06)	0.66 (.03)	0.93 (.06)	0.67 (.03)
	Rear leg	0.55 (.13)	0.34 (.03)	0.60 (.15)	0.37 (.03)
Ardha chandrasana (half moon)	Balancing leg	1.04 (.03)	0.84 (.05)	1.04 (.03)	0.84 (.05)
Vrksasana (tree)	Balancing leg	1.10 (.03)	0.97 (.02)	1.10 (.03)	0.97 (.02)
Utthita hasta padangusthasana (standing big toe)	Balancing leg	1.05 (.02)	0.99 (.00)	1.05 (.02)	0.99 (.00)
Garudasana (eagle)	Balancing leg	1.08 (.02)	0.99 (.02)	1.07 (.02)	0.99 (.02)
Bakasana (crow)	Balancing arms	1.05 (.05)	0.73 (.13)	1.06 (.05)	0.74 (.13)

Table V. — Mean ground reaction forces (GRF) normalized to BW for postures with significant differences due to gender (p-value).

Hatha yoga posture	Limb(s) measured	Gender	Maximum vertical GRF	Mean vertical GRF	Maximum resultant GRF	Mean resultant GRF
Urdva mukha svanasana (upward facing dog)	Arms	Female	0.85		0.86	
	Arms	Male	0.89		0.89	
			(.008)		(.02)	
Dandasana (plank)	Arms	Female			0.89	
	Arms	Male			0.99	
	Feet	Female		0.34	(.03)	
	Feet	Male		0.32		
				(.02)		
Pincha mayurasana (dolphin)	Arms	Female	0.71		0.72	
	Arms	Male	0.74		0.75	
			(.01)		(.02)	
Adho mukha svanasana (downward facing dog)	Arms	Female		0.45		0.50
	Arms	Male		0.49		0.53
	Feet	Female	0.65	(.03)	0.71	(.02)
	Feet	Male	0.59		0.65	
			(.03)		(.008)	
Virabhadra-sana (crescent)	Forward leg	Female	0.92	0.58	0.94	0.61
	Forward leg	Male	1.02	0.61	1.04	0.64
			(.04)	(.06)	(.05)	(.03)
	Rear leg	Female		0.41		0.44
	Rear leg	Male		0.37		0.40
				(.02)		(.03)

Figure 1.—Condition 1. Force plate perimeter is outlined on yoga mat and subject begins sequence by standing over the force plate. Forces are measured in either one or both lower and upper extremities.

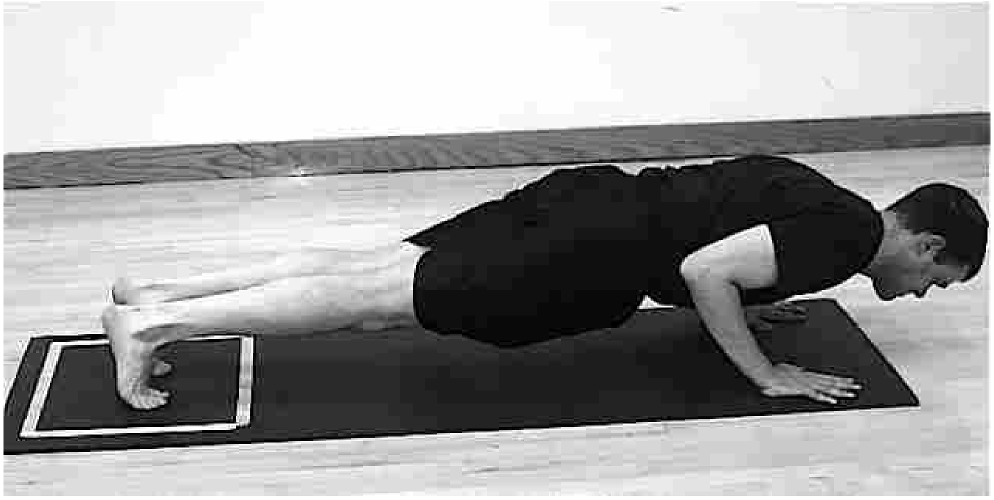

Figure 2.—Condition 2. Subject begins sequence standing in front of force plate and steps back with one or both lower extremities.

Figure 3a.—Tadasana (mountain). Subject begins with arms at sides.

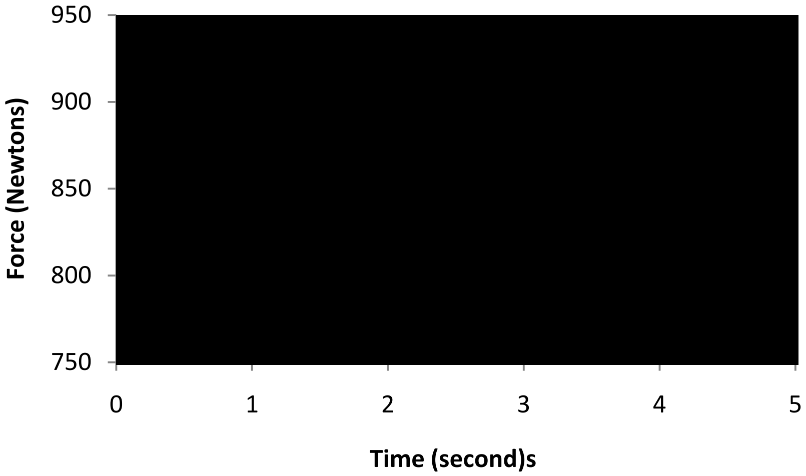

Figure 3b.—Tadasana, condition 1. Maximum vertical ground reaction force (Mxvgrf). Dual peaks reflect force from lower extremities as arms reach overhead.

Figure 4a.—Uttanasana (forward fold). Subject flexes at the hip and brings arms to floor.

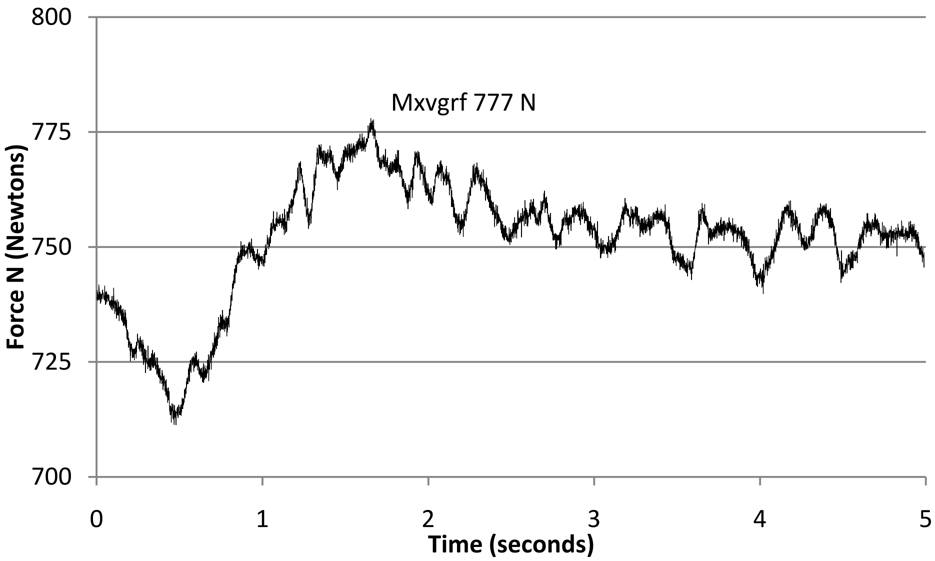

Figure 4b.—Uttanasana, condition 1. Maximum force achieved as subject shifts weight into heels and upper body approaches the floor.

Figure 5a.—Urdva mukha uttanasana (monkey). Subject extends spine, lifting torso away from legs.

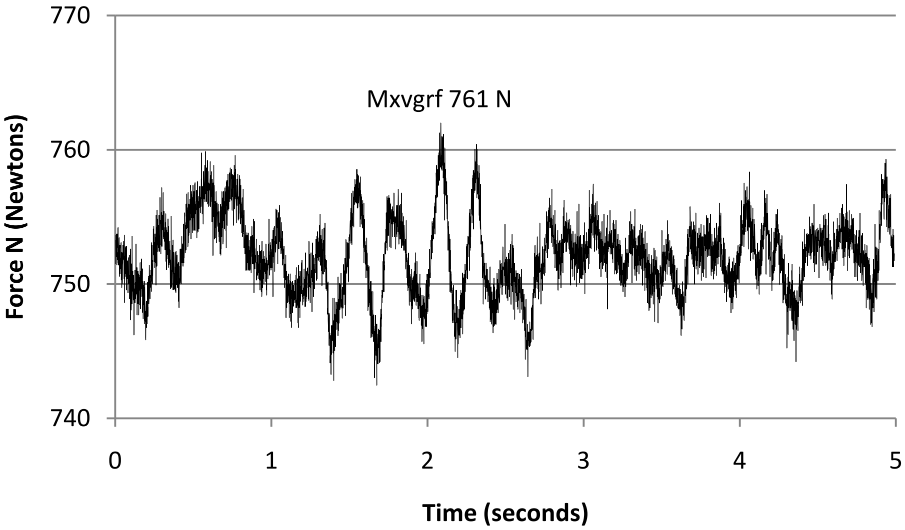

Figure 5b.—Urdva mukha uttanasana, condition 1. Force curve captures numerous accelerations. Weight shifts from ball of foot to heel as torso lifts. More flexible subjects will straighten legs and touch the floor.

Figure 6a.—Dandasana (plank). Subject places hands on floor and steps from uttanasana into position.

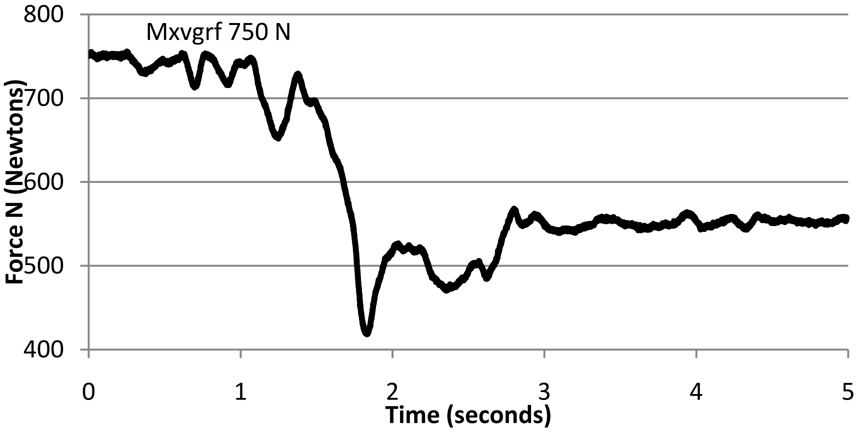

Figure 6b.—Dandasana, condition 1. Maximum force in upper extremities decreases once feet are in place.

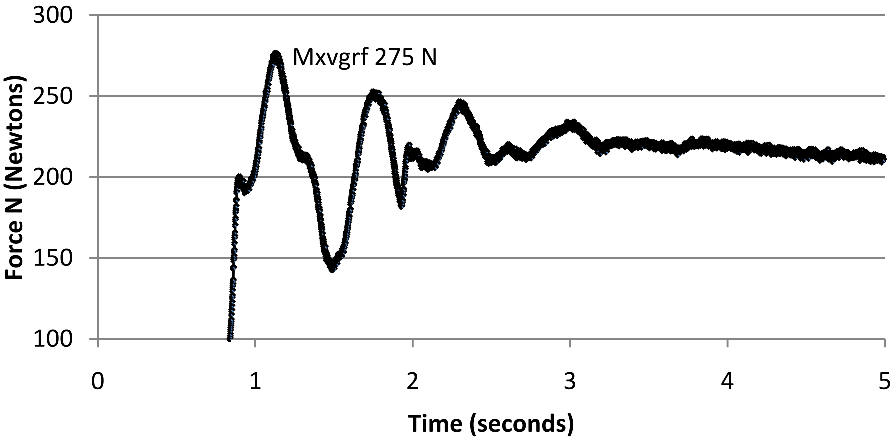

Figure 6c.—Dandasana, condition 2. Peaks in force reflect movement of feet into position and stabilization of weight in lower extremities.

Figure 7a.—Chaturanga dandasana (crocodile). Subject lowers body toward the floor.

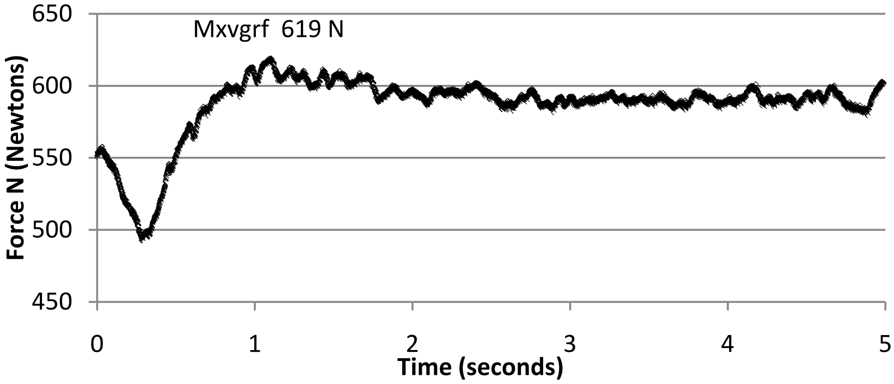

Figure 7b.—Chaturanga, condition 1. Upper extremity force diminishes as body lowers with gravity. Maximum force is generated through arms at cessation of descent.

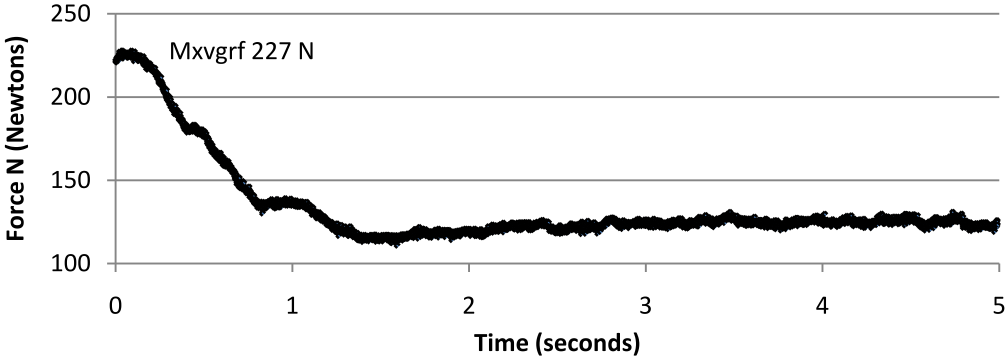

Figure 7c.—Chaturanga, condition 2. Maximum force occurs as body begins to lower toward floor, followed by stable force measured at the feet.

Figure 8a.—Urdva mukha svanasana (upward facing dog). Subject pushes upward from chaturanga. Hips and thighs contract and lift away from the floor as weight is supported in hands and feet.

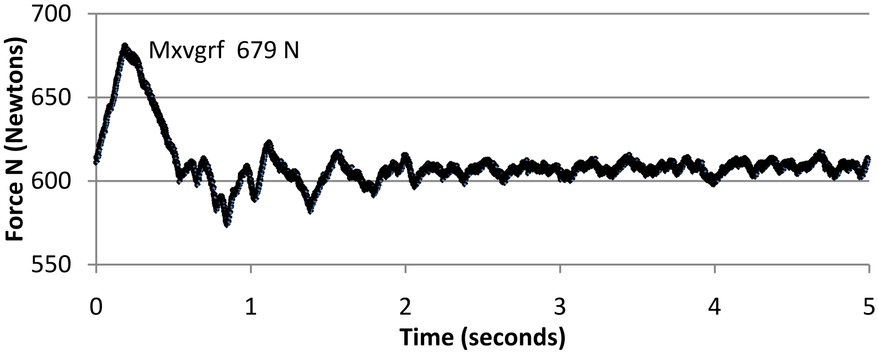

Figure 8b.—Urdva mukha svanasana, condition 1. Maximum force is generated with upper extremity extension which lifts torso upward.

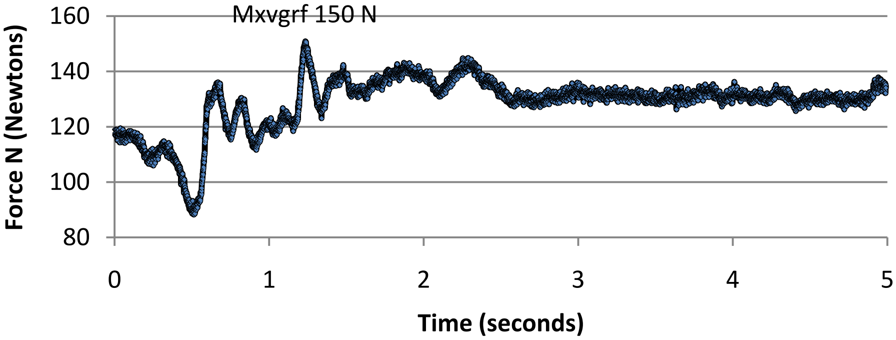

Figure 8c.—Urdva mukha svanasana, condition 2. Multiple peaks reflect changing foot position from balls to tops of feet, followed by weight stabilization in lower extremities

Figure 9a.—Adho mukha svanasana (downward facing dog).

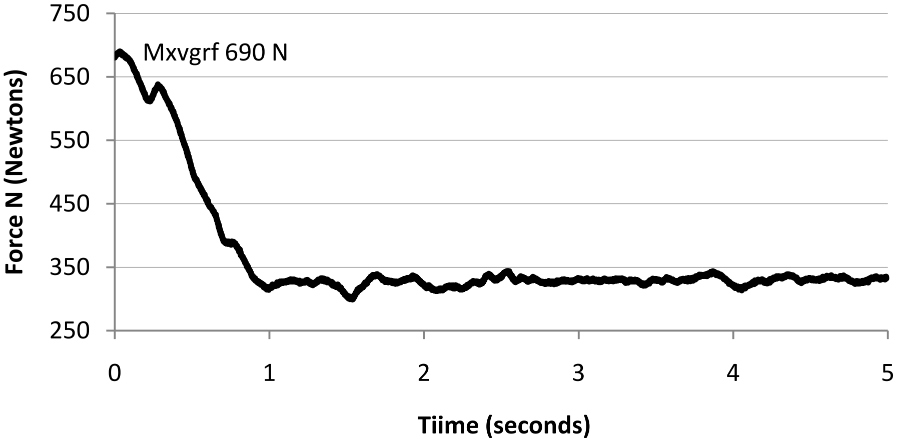

Figure 9b.— Adho mukha svanasana, condition 1. Maximum force generated in upper body as subject lifts hips upward and pushes against floor.

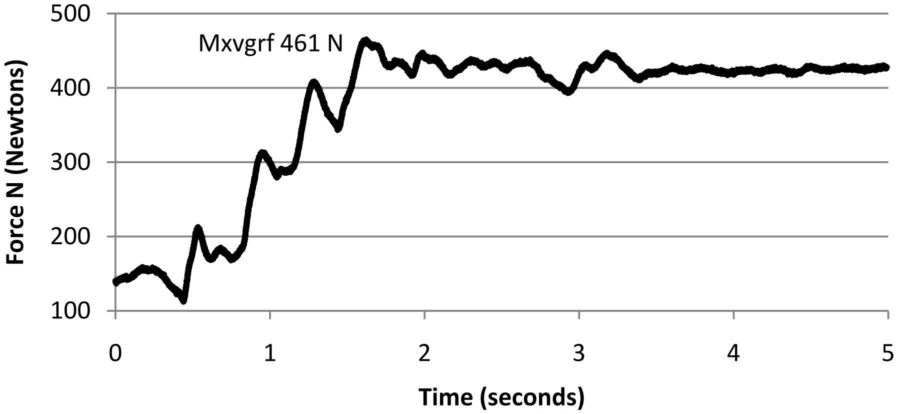

Figure 9c.— Adho mukha svanasana, condition 2. Upward curves reflect weight shifting as hips lift upward and more body weight is supported in the lower extremities.

Figure 10a.—Uttanasana (forward fold). Subject bends knees and leaps to front of mat from adho mukha svanasana.

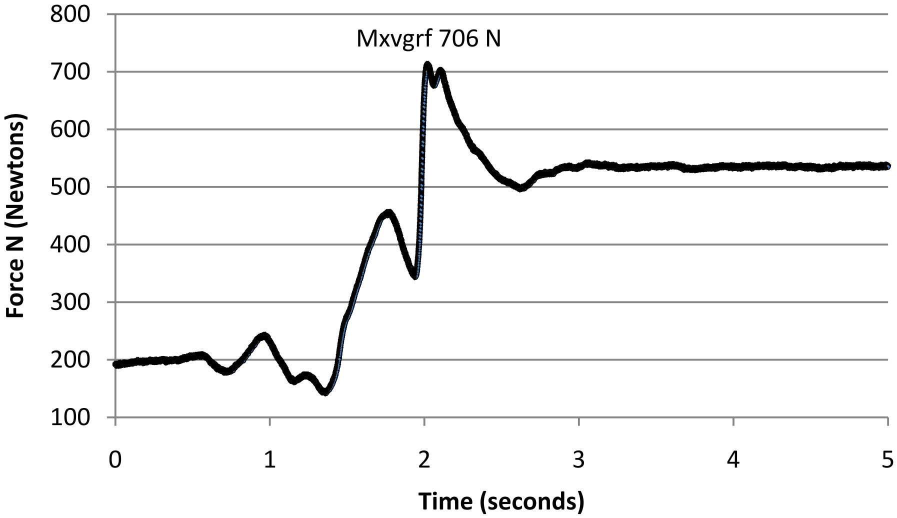

Figure 10b.— Uttanasana, condition 1. Lower portion of curve is force exerted by the hands prior to subject leaping forward. First peak is force generated in upper extremities as lower extremities are propelled from the floor, and second peak is the landing.

Figure 11a.—Utkatasana (chair). Subject bends knees and brings hands together at chest level.

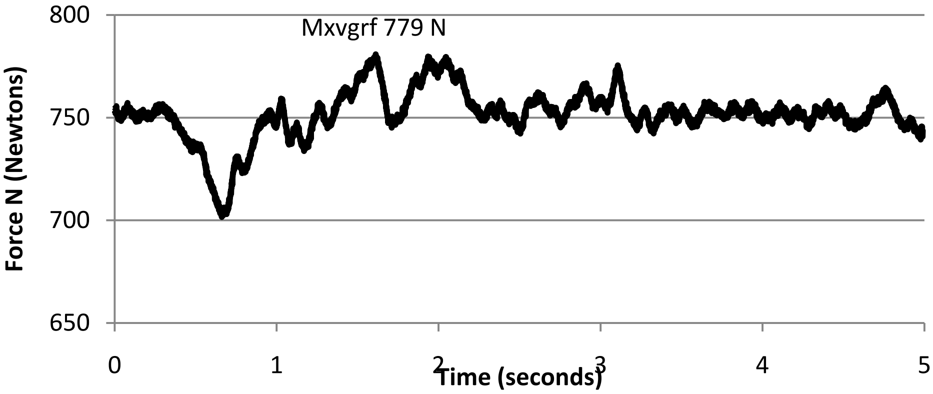

Figure 11b.— Utkatasana, condition 1. Peaks in force curve reflect acceleration into position and forces generated in both feet.

Figure 12a.—Parivrtta utkatasana (twisting chair). Subject flexes further at the knee and twists torso to one side.

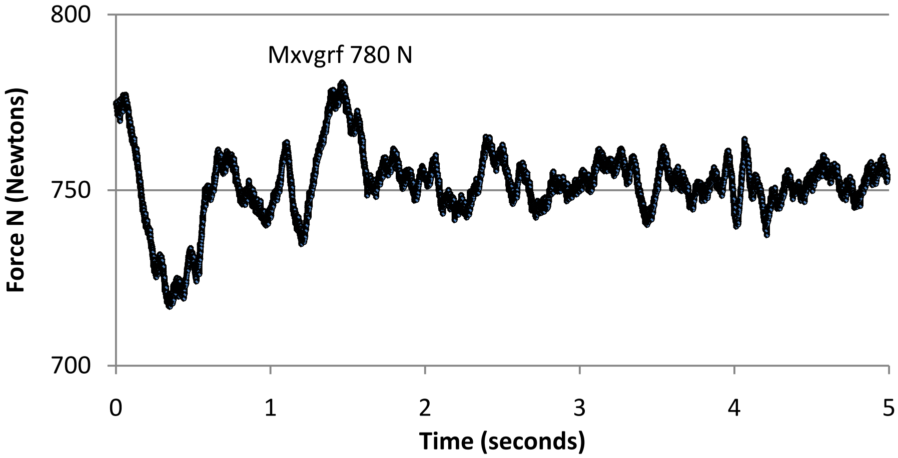

Figure 12b.— Parivrtta utkatasana, condition 1. Force curve reflects small adjustments in position of feet to maintain balance.

Figure 13a.—Ardha uttanasana (airplane). Subject straightens legs and extends arms backward.

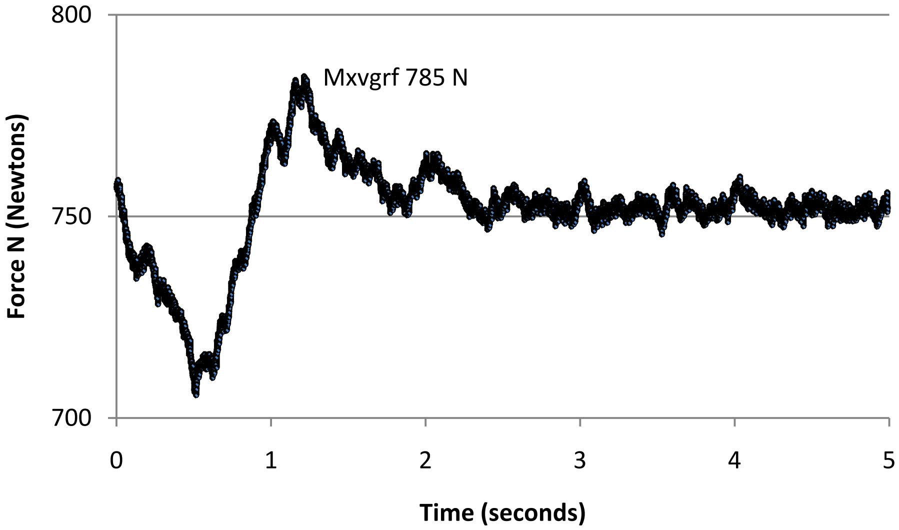

Figure 13b.— Ardha uttanasana, condition 1. Maximum force occurs as legs are straightened and body mass shifts into balls of the feet.

Figure 14a.—Virabhadrasana 1 (warrior). Subject steps back with one foot and reaches arms overhead.

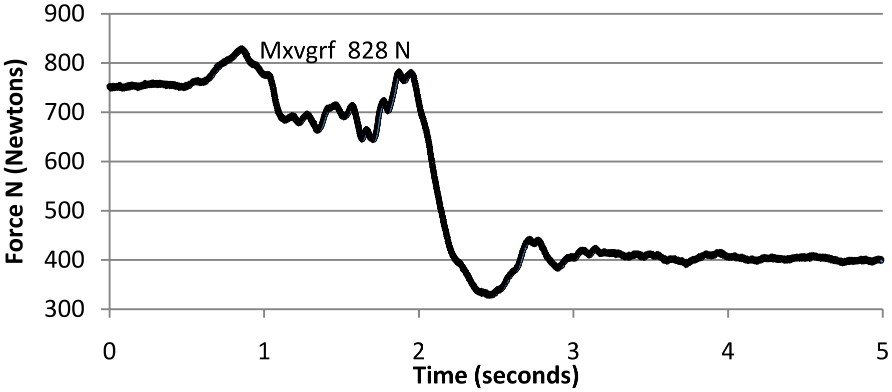

Figure 14b. Virabhadrasana 1, condition 1. First peak is from forward leg as subject steps back with the other. Second peak is force generated as forward leg accepts weight. Force curve drop reflects lowering with gravity into the lunge.

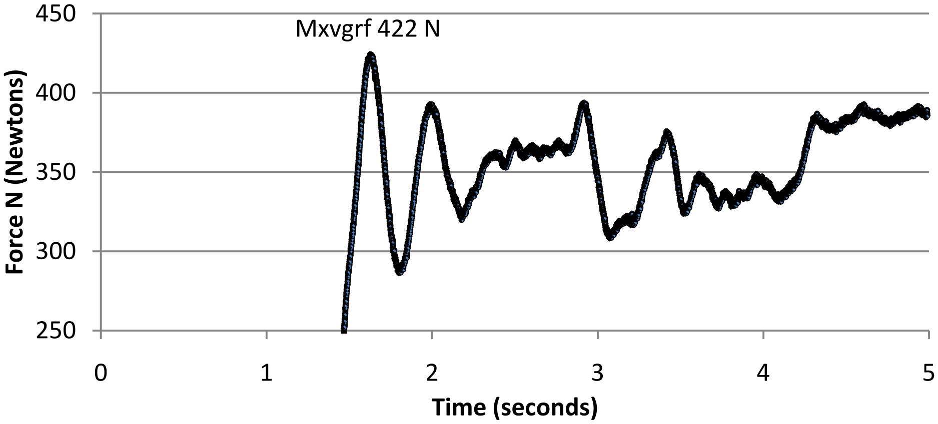

Figure 14c.— Virabhadrasana 1, condition 2. Maximum force comes from rear leg landing.

Figure 15a.—Virabhadrasana 3 (warrior). Subject shifts body mass into forward leg and lifts rear leg off the floor.

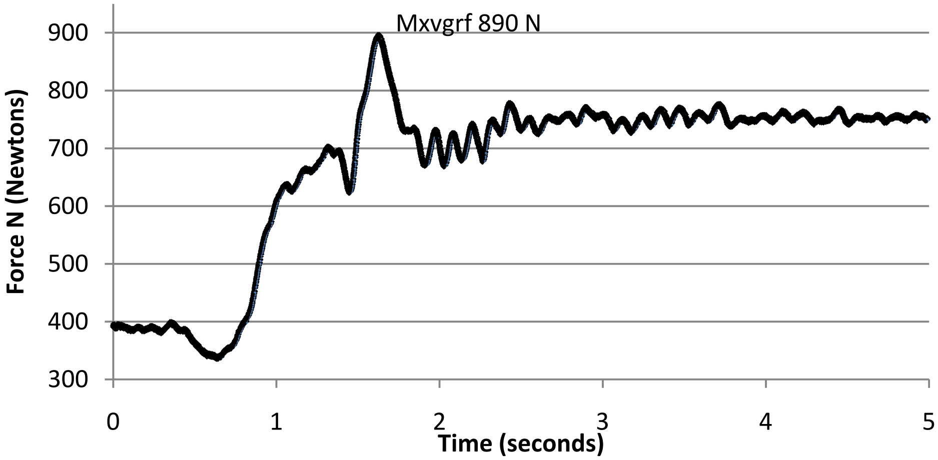

Figure 15b.— Virabhadrasana 3, condition 1. Maximum force occurs in stepping onto balancing leg, followed by stabilization.

Figure 16a.—Virabhadrasana 2 (warrior). Subject steps back with one leg and assumes a deep lunge.

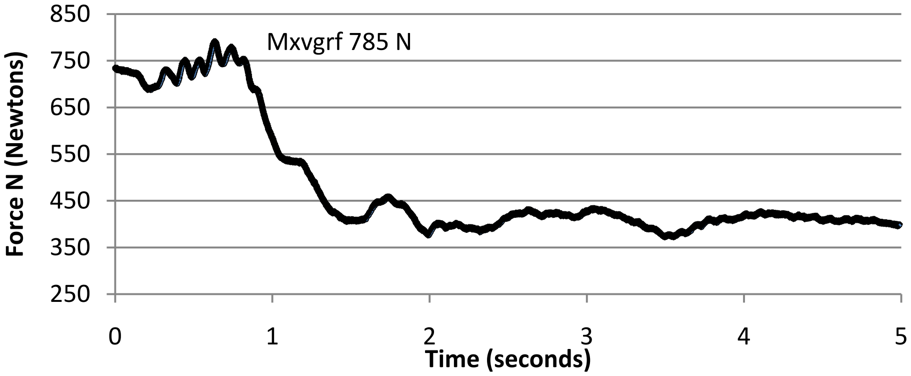

Figure 16b.— Virabhadrasana 2, condition 1. Peak force occurs in the front leg as body mass accelerates to upright position, then decreases as subject lunges.

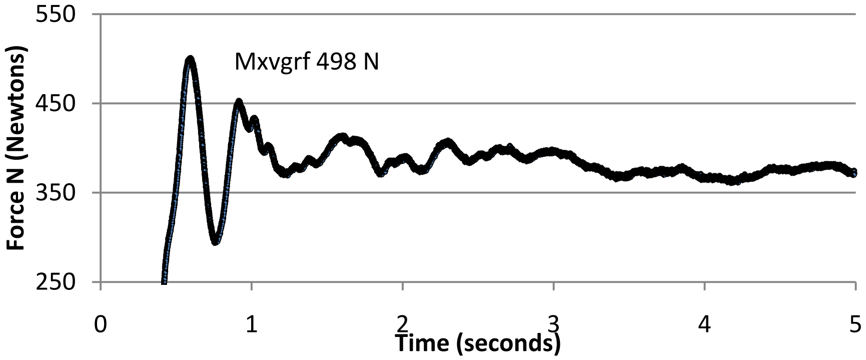

Figure 16c.— Virabhadrasana 2, condition 2. Maximum force generated during landing, followed by second peak representing correction of foot placement and stabilization.

Figure 17a.—Trikonasana (triangle). Subject straightens lower extremities, twists torso and lifts one arm.

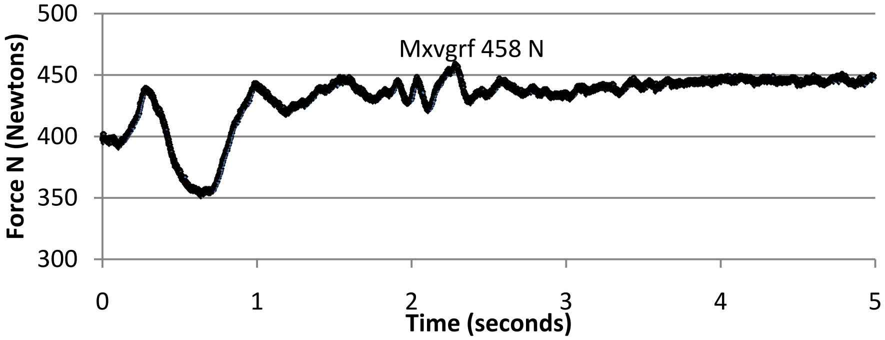

Figure 17b.— Trikonasana, condition 1. Maximum force occurs in forward leg as subject ascends from lunge.

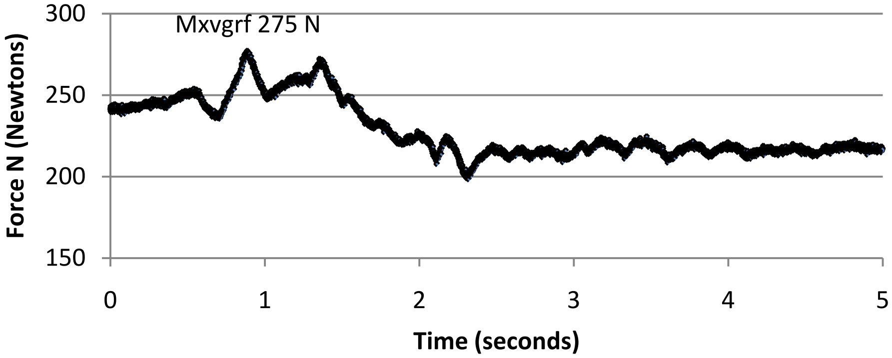

Figure 17c.— Trikonasana, condition 2. Maximum force generated in rear leg as body mass is balanced between lower extremities.

Figure 18a.—Virabhadrasana (reverse). Subject lunges and reaches one arm up and back.

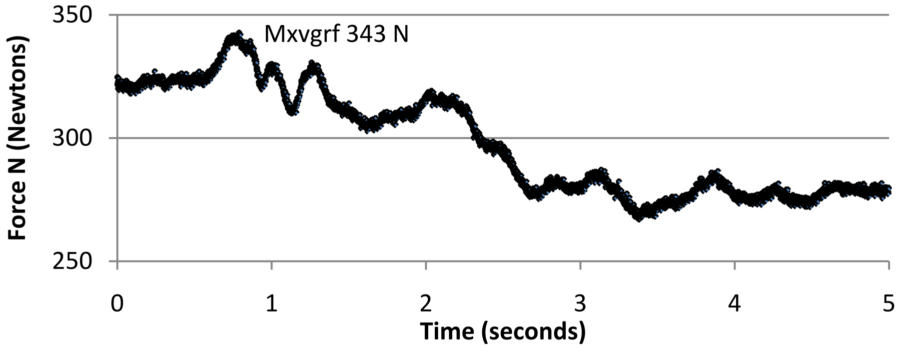

Figure 18b.— Virabhadrasana, condition 1. Maximum force generated with acceleration from trikonasana to the lunge.

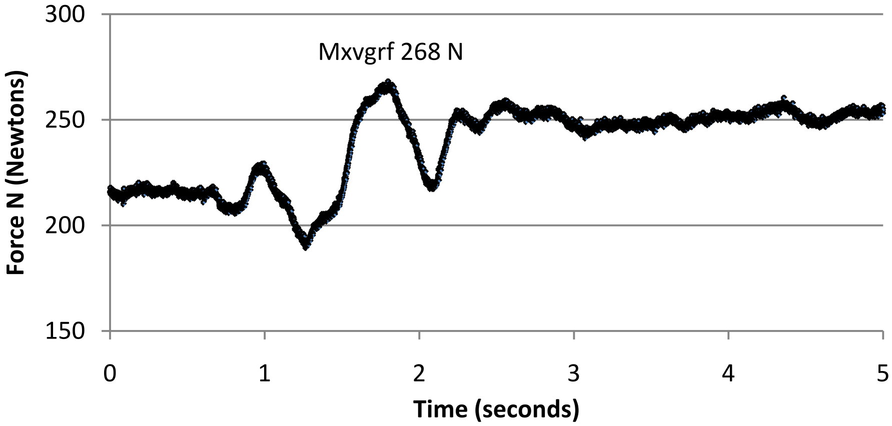

Figure 18c.— Virabhadrasana, condition 2. Maximum force occurs as body weight shifts toward rear.

Figure 19a.—Utthita parsvakonasana (side angle). Subject brings one arm to thigh and other arm overhead.

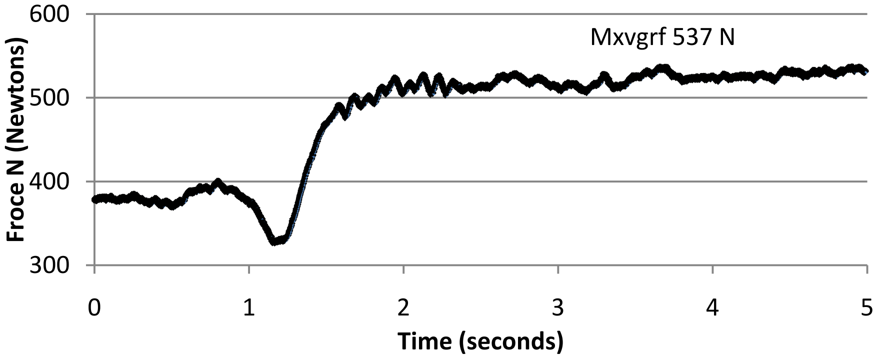

Figure 19b.— Utthita parsvakonasana, condition 1. Maximum force is generated as body mass shifts forward.

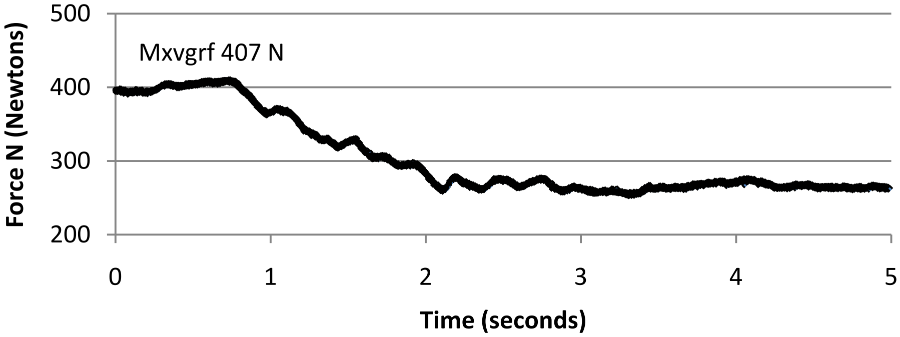

Figure 19c.— Utthita parsvakonasana, condition 2. Maximum force measured at rear leg as body mass shifts forward.

Figure 20a.—Baddha parsvakonasana (bound side angle). Subject wraps arms around torso and deepens lunge.

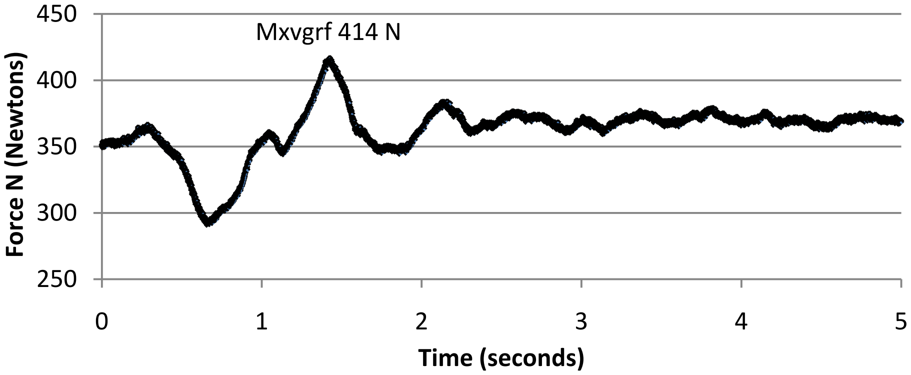

Figure 20b.—Baddha parsvakonasana, condition 1. Maximum force is generated with change in center of mass.

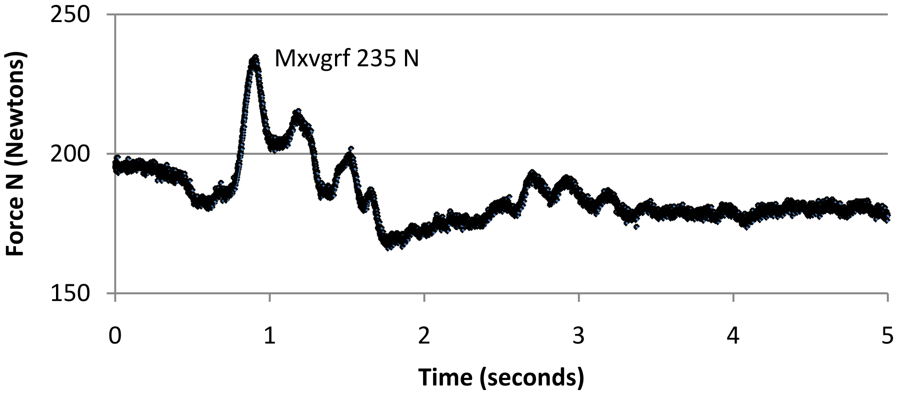

Figure 20c.—Baddha parsvakonasana, condition 2. Peak force occurs with readjustment of back foot.

Figure 21a.—Vasisthasana (side plank). Subject supports weight with one upper extremity and both lower extremities (feet stacked).

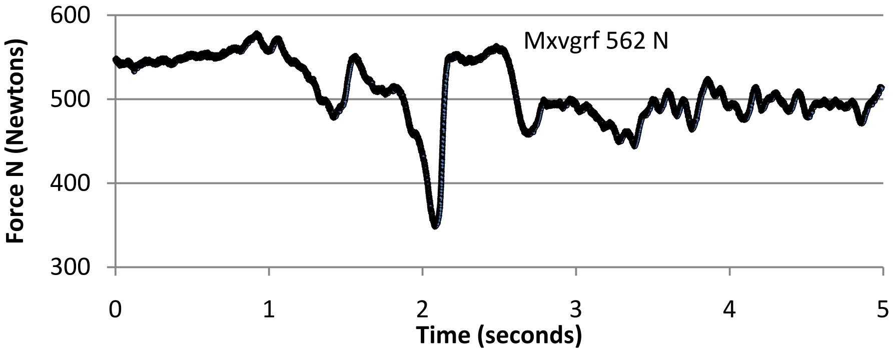

Figure 221b.—Vasisthasana, condition 1. Low portion of force curve is removal of foot from previous posture. Maximum force occurs with arm placement.

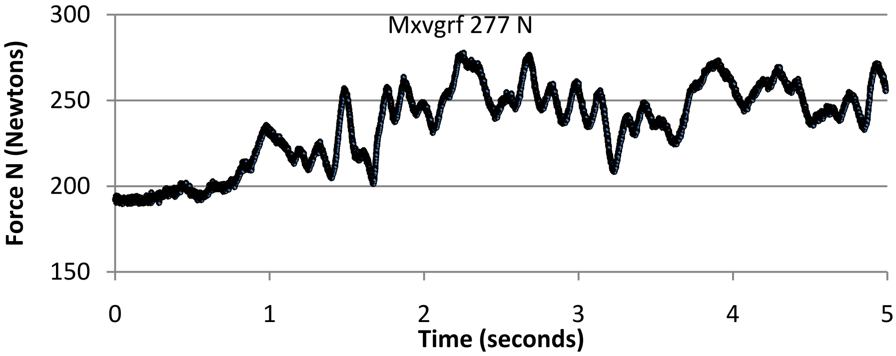

Figure 21c.—Vasisthasana, condition 2. Variations in force curve represent adjustments to balance in the lower extremities.

Figure 22a.—Vasisthasana (side plank variation with leg lifted).

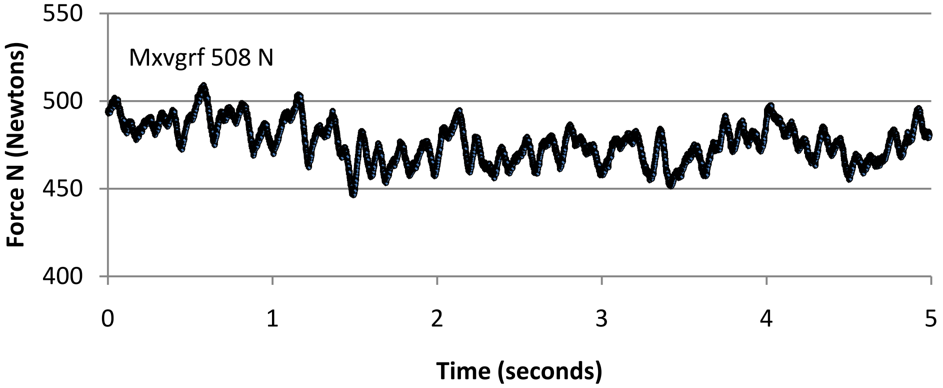

Figure 22b.—Vasisthasana, condition 1. Force curve represents balance adjustment through upper extremity.

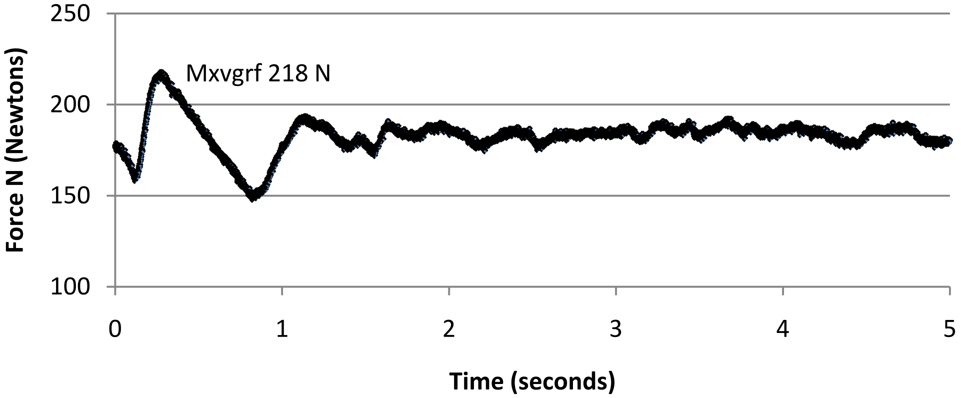

Figure 22c.—Vasisthasana, condition 2. Maximum force as upper leg is lifted and lower leg exerts greater force to support body weight, followed by stabilization.

Figure 23a.—Pincha mayurasana (dolphin). Subject places both arms and feet onto mat.

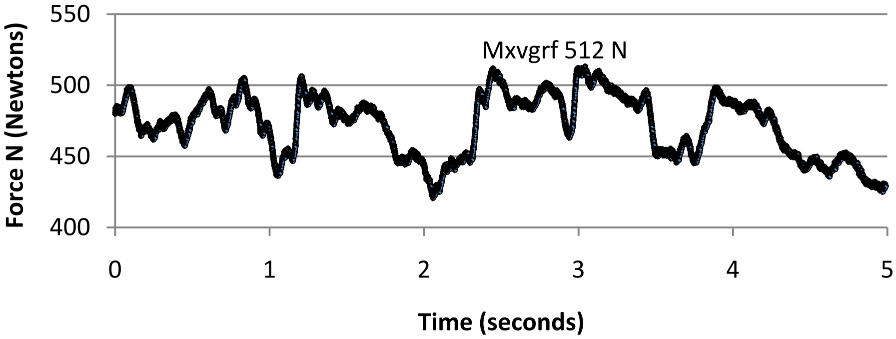

Figure 23b.—Pincha mayurasana, condition 1. Variations in force curve represent movement of upper extremities into position and acceleration of body mass as hips are lifted.

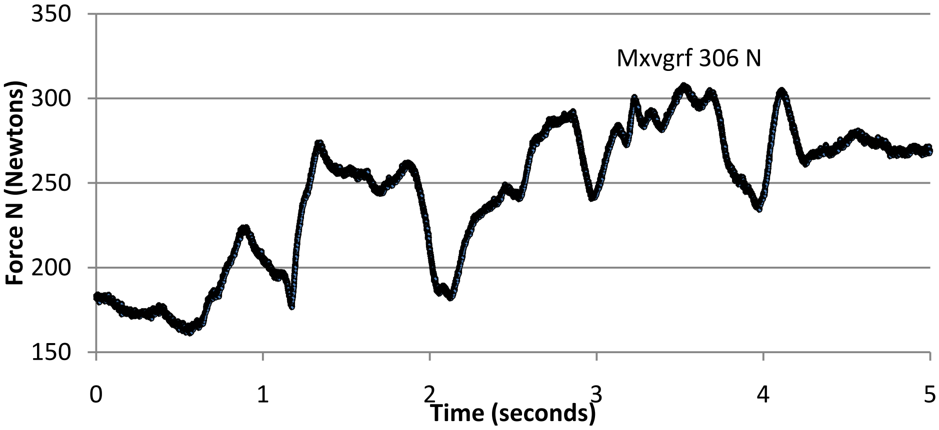

Figure 23c.—Pincha mayurasana, condition 2. Various peaks represent movement of feet into position. Maximum force occurs as body mass accelerates and hips are lifted.

Figure 24a.—Virabhadrasana (crescent). Subject moves from adho mukha svanasana (downward facing dog) by bringing one leg forward and assuming a lunge with arms reaching up and backward.

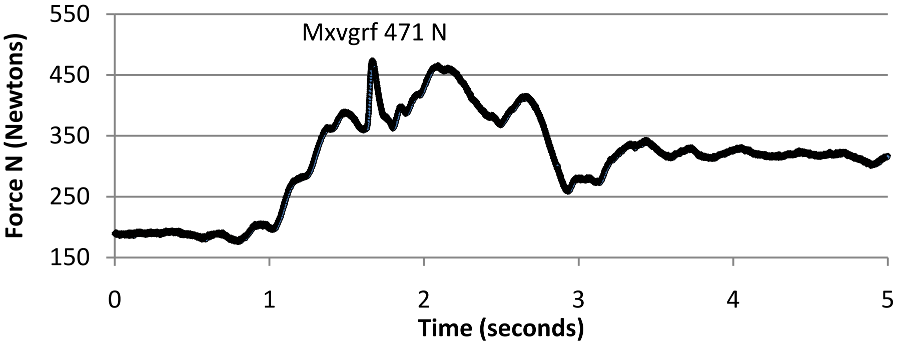

Figure 24b.—Virabhadrasana, condition 1. Maximum force occurs in forward leg upon landing.

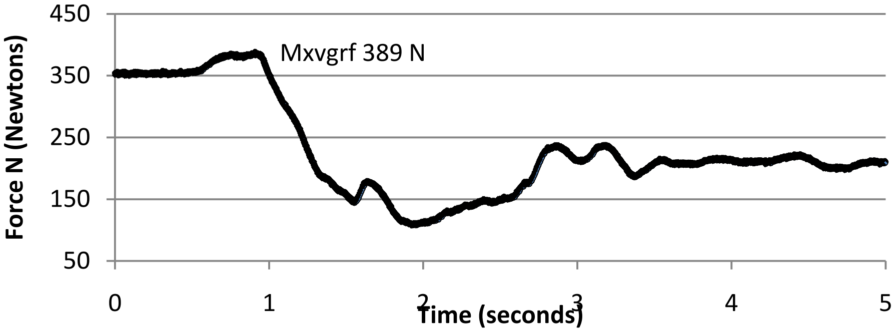

Figure 24c.—Virabhadrasana, condition 2. Maximum force in rear leg occurs as weight is supported during initial propulsion of front leg.

Figure 25a.—Parivrtta parsvakonasana (twisting angle/warrior). Subject brings hands to chest and twists over front leg.

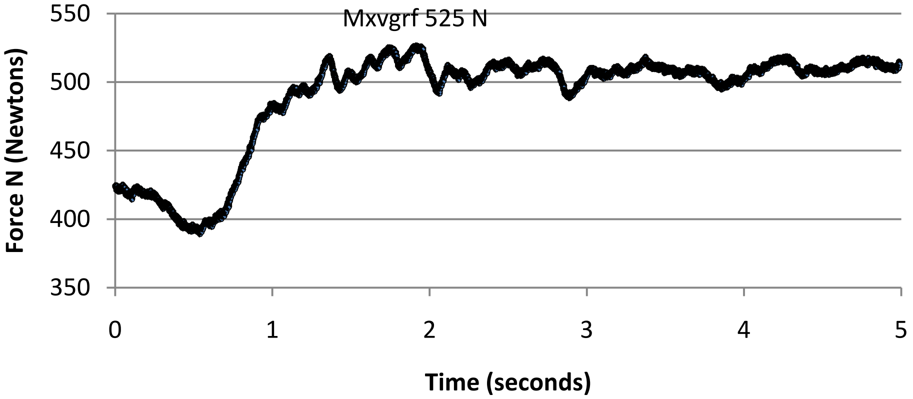

Figure 25b.—Parivrtta parsvakonasana, condition 1.Maximum force occurs with movement into twist.

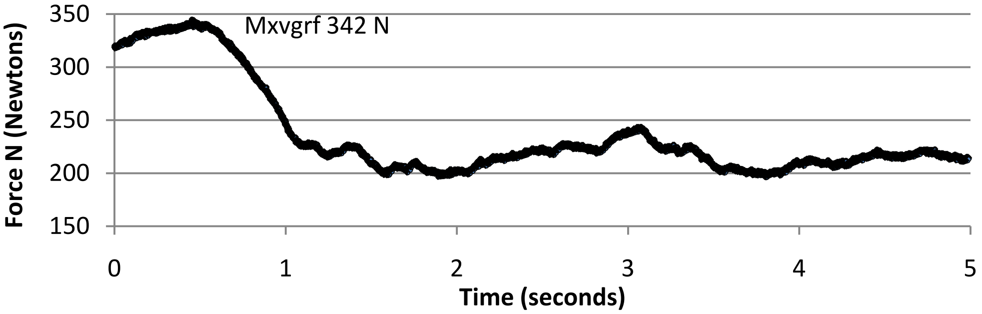

Figure 25c.—Parivrtta parsvakonasana, condition 2. Peak force in rear foot with shift in body mass decreases as body lowers into lunge.

Figure 26a.—Parsvottanasana (pyramid). Subject straightens lower extremities, placing feet flat, and brings head toward forward leg.

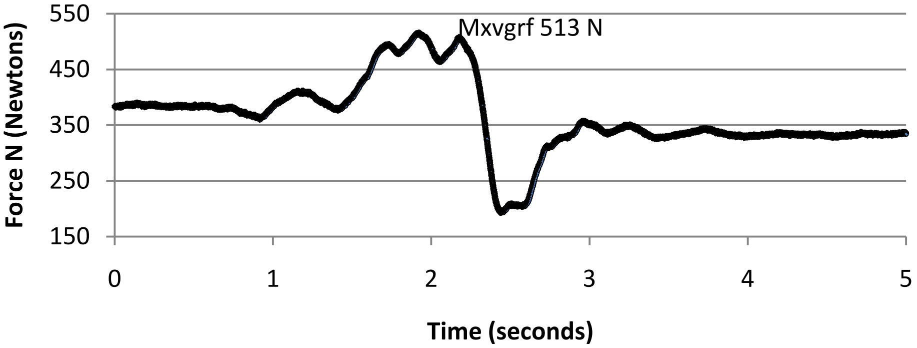

Figure 26b.—Parsvottanasana, condition 1. Maximum force occurs in front leg and then decreases as torso descends.

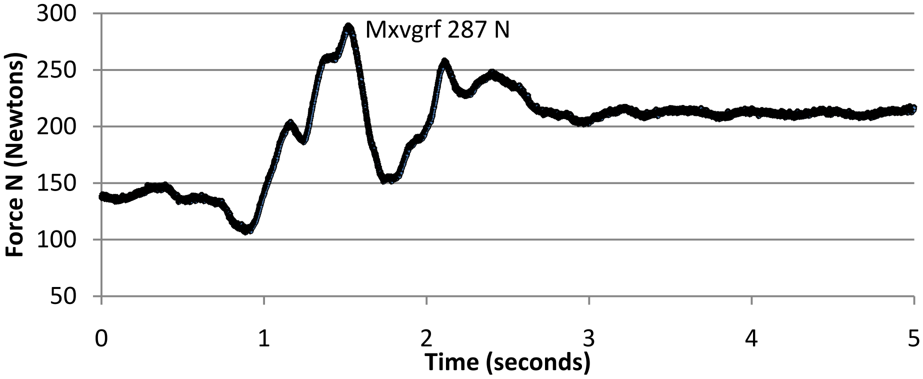

Figure 26c.—Parsvottanasana, condition 2. Maximum force occurs when subject replaces foot flat onto floor.

Figure 27a.—Ardha chandrasana (half moon). Subject balances on forward leg assisted by one upper extremity which is placed in front of the force plate.

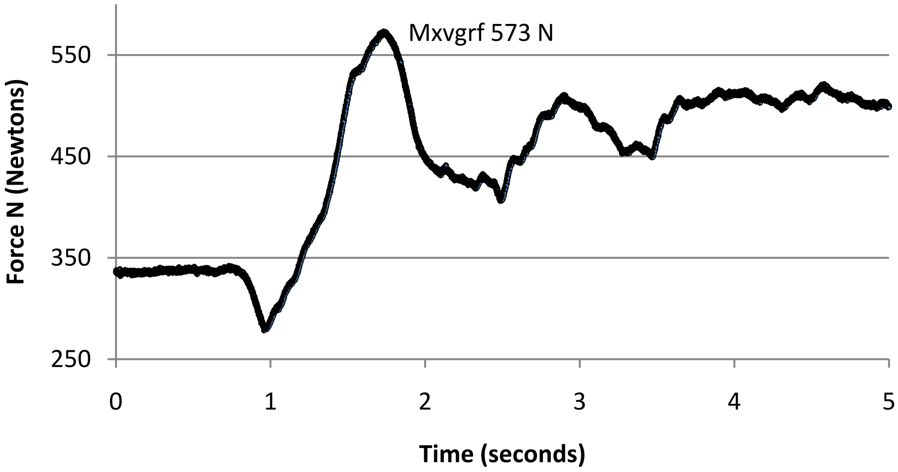

Figure 27b. —Ardha chandrasana, condition 1. Maximum force generated as body mass accelerates over forward leg and rear leg is lifted, followed by stabilization of the posture.

Figure 28a.—Vrksasana (tree). Subject moves to upright position and brings one foot to thigh.

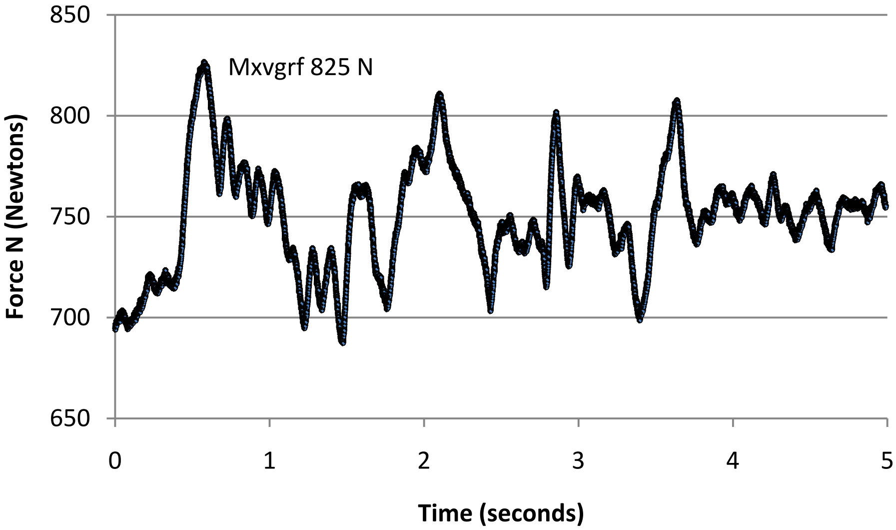

Figure 28b.—Vrksasana, condition 1. Vacillations in force curve reflect movement into posture and stabilization.

Figure 29a.—Utthita hasta padangusthasana (standing big toe). Subject grasps big toe and extends arms and legs.

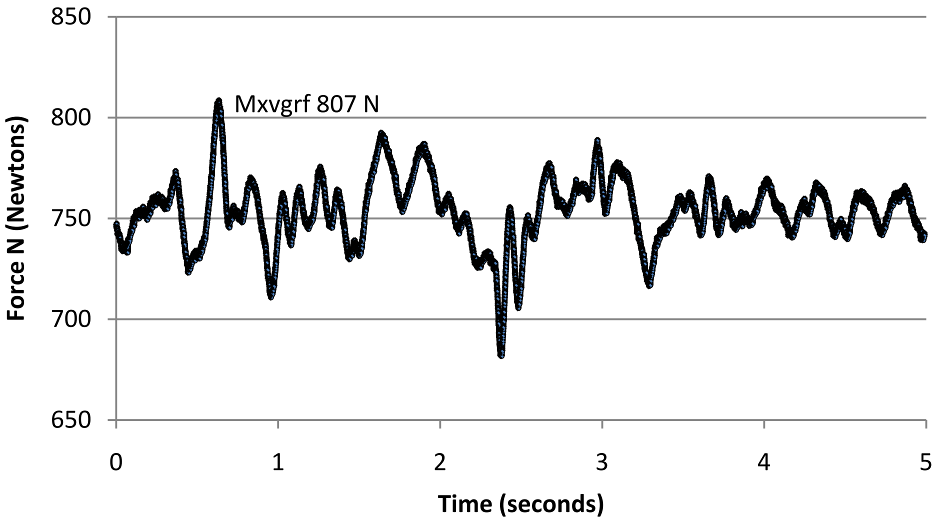

Figure 29b.—Utthita hasta padangusthasana, condition 1. Vacillations in force curve represent movement into and maintenance of posture.

Figure 30a.—Garudasana (eagle). Subject crosses one leg over the other and crosses arms in front of chest.

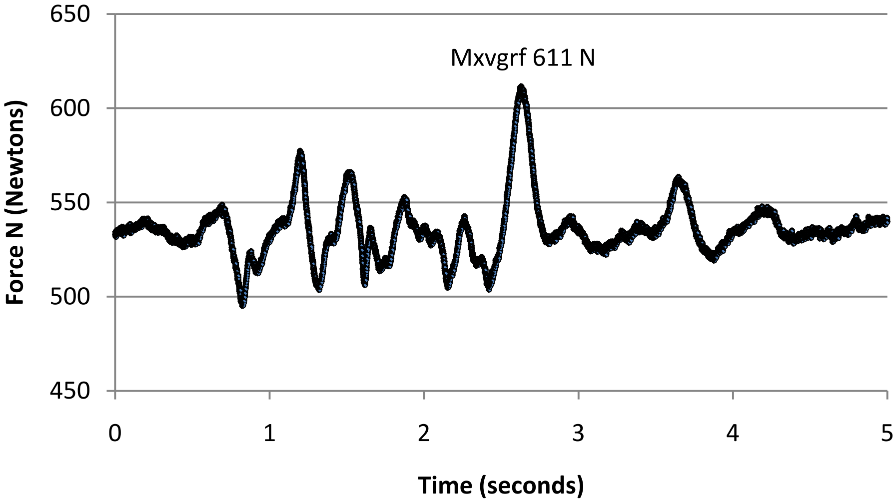

Figure 30b.—Garudasana, condition 1. Maximum force occurs as arms come to chest height shifting body mass over supporting leg.

Figure 31a.—Bakasana (crow). Subject steps off force plate and brings hands to floor.

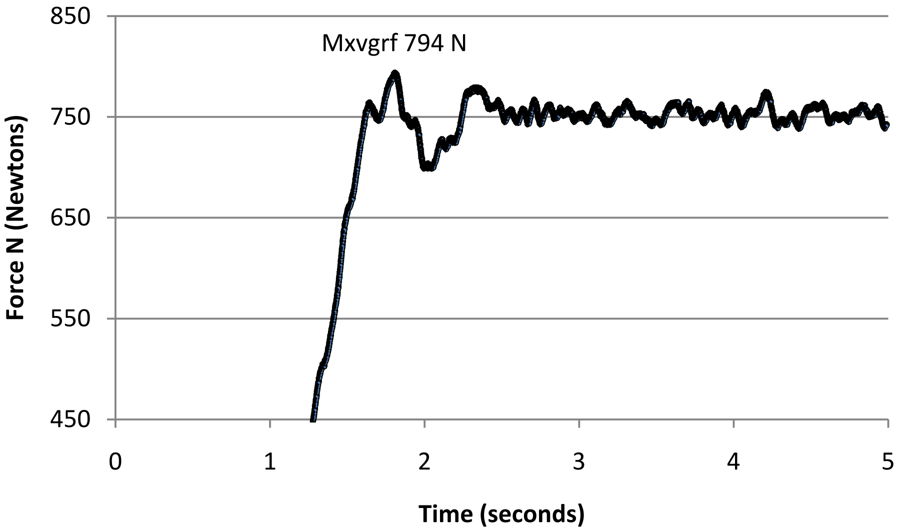

Figure 31b.—Bakasana, condition 1. Maximum impact is generated as body mass is supported by upper extremities.

Appendix A Prospectus

Chapter 1

Introduction

Yoga is a popular form of exercise that is accessible in small private studios, fitness clubs, and recreation centers across the nation. The most commonly practiced form of yoga is hatha yoga, which combines three key features; the postures (called asanas), the mind, and the breath (Raub, 2002).

Yoga practitioners (yogis) claim that yoga reduces stress (Cole, 2004), relieves headaches (Pirtle, 2004), and increases strength and flexibility (Ward, 2003). Yoga may also reduce pain and disability in osteoarthritis of the knee (Kolasinski, et al. 2005) and effectively treat some symptoms of carpal tunnel syndrome (Garfinkel, et al. 1998). Some assert that practicing yoga promotes healthy bones and prevents osteoporosis (Abbott, 2000; Maddern, 2000; Sparrowe, 2004).

Statement of the Problem

Is yoga indeed beneficial to bone health? Yogis seem to feel confident making this claim since many hatha yoga asanas are weight bearing. These include standing and arm balancing postures as well as strengthening postures performed with one to four limbs for support. Although there is little or no jumping in the typical yoga session, muscles and joints are loaded intensely using body weight, gravity, and varying amounts of time in sustained holds, thus employing concentric, eccentric, and isometric contractions. However, the effect of yoga’s weight bearing asanas on bone health has not been examined, nor are there any studies which illustrate yoga's force generating qualities.

Exercise exerts its effects on the bones by the force of gravity and the force of muscle contractions (Mayoux-Benhamou, Leyge, Roux, & Revel, 1999). Resistance or weight training regimens using free weights or variable resistance machines suggest that the tensile forces exerted on the muscles are sufficient to improve bone mineral density (BMD) at various skeletal sites in men and women (Nelson, Fiatarone, & Morganti, 1994; Ryan et al., 2004). Likewise, high and low impact exercise programs or combinations of the two increased proximal femur BMD in men and women over 50 (Welsh & Rutherford, 1996); improved BMD at numerous sites in premenopausal women (Heinonen, Kannus, & Sievanen, 1996); and significantly increased BMD of the whole body, leg, and spine in postmenopausal women (Kohrt, Ehsani & Birge, 1997). Low impact weight bearing exercises combined with a weight lifting program maintained BMD of the spine and hip in postmenopausal women (Stengel et al., 2005) and walking at sufficient speed improved BMD of the legs and total body (though not significantly) in postmenopausal women (Borer, Fogleman, Gross, LaNew & Dengel, 2007).

Yoga shares common features with all but the high impact exercises. Instead of using weights or resistance machines, the weight of the body is supported by the hands, arms, feet and legs. Joints and bones are loaded as the limbs are used to support the weight of the body against gravity. Furthermore, in a typical hatha yoga class, force is generated as participants accelerate into and out of the asanas, change their center of mass, and transfer weight between one or more limbs at a time. The ground reaction forces (GRF) generated by these movements might be similar to those measured in low impact, strength training exercise, and walking regimens that have been shown to have a beneficial effect on bone mineral density (Bassey& Ramsdale, 1995; Bassey, Rothwell, Littlewood, & Pye, 1998; Borer et al., 2007; Grove & Londeree, 1992;

Heinonen et al., 1996).

Statement of Purpose

The aim of this descriptive study is to answer the question, “Do hatha yoga postures generate ground reaction forces comparable to other forms of exercise that are shown in the literature to benefit bone health?”

This question will be answered by

1. Collecting ground reaction force data from 28 common hatha yoga postures using a force platform;
2. Comparing these forces with those that have been identified in studies of high and low impact exercise programs.

Hypothesis

Ground reaction forces in a hatha yoga practice will be similar to low impact forces of less than two times body weight. The null hypothesis is that hatha yoga asanas will generate ground reaction forces greater than or equal to two times body weight.

Definition of Terms

According to one study, high impact exercises are those that generate a ground reaction force greater than or equal to two times the body weight (Grove & Londeree, 1992). Low impact exercises generate a ground reaction force less than two times the body weight. There is currently no data on yoga’s force generating characteristics; thus, this descriptive study will provide original information on the subject.

Delimitations

Since both men and women practice yoga, men and women who are either yoga instructors or who have more than three years experience practicing yoga will be recruited for their expertise and accuracy in executing the hatha yoga postures. Experienced yogis will also possess the needed stamina to perform the sequence of asanas numerous times during the data collection session. The same sequence of asanas will be performed by each subject and will consist of 28 hatha yoga postures that would typically be incorporated into a yoga class held at a studio or fitness center and attended by beginner or intermediate level participants.

Assumptions

McNair and Prapavessis (1999) conducted a study of adolescent boys and girls who jumped from a height of 0.3 meters onto a force plate and found no significant differences in the GRF measured between the two groups. Thus, it is assumed that each subject will generate a similar range of ground reaction forces normalized to his or her body weight. It is also assumed that the force plates are reliable and accurate in their measurements.

Limitations

The study will not measure ground reaction forces generated by seated and supine flexibility poses which can make up a significant portion of a hatha yoga session. Likewise, other vigorous forms of hatha yoga, which require a higher level of strength and expertise, will not be studied.

Chapter 2

Review of Literature

Terms used in an extensive data base search included ground reaction force, bone density, bone health, high impact, low impact, osteoporosis, weight bearing, weight training, yoga, and exercise.

Studies Comparing Exercise Mode and Bone Density

Numerous studies have been undertaken to determine what types of exercise programs or activities are most likely to benefit bone health. Due to the high incidence of osteoporosis and related fractures, especially in older women, researchers are interested in determining how to enhance bone health in youth in order to offset the losses of older age, and to determine effective exercise regimens to either improve or maintain bone health in women and men as they age, or at least to slow the rate of bone mineral loss. Results of these studies are mixed, and there is no consensus on either the best type of exercise or the appropriate dose to achieve desired effects.

A few studies include measurements of GRF produced by the exercise regimens employed, and thus identify possible doses or intensities of exercise that may be beneficial to bone health. Table 1 summarizes a group of such trials. Those studying postmenopausal women showed that bone mineral density (BMD) was maintained or increased by both low and high impact exercise regimens (Borer et al., 1997; Grove & Londeree, 1992) or that there was no effect (Bassey & Ramsdale, 1995). For pre-menopausal women, high impact exercises proved effective in increasing BMD at various sites (Heinonen et al., 1996; Bassey et al., 1998).

Kohrt, Ehsani & Birge, (1997) defined their two exercise trials according to how stress was exerted on the skeleton; namely through either GRF with exercises such as walking or jogging, or by joint reaction forces using free weights and machines or rowing. In this trial, only the GRF exercise program, which exerted forces through the lower limbs, improved BMD at the femoral neck. However, both types of exercise programs produced significant increases in BMD of the whole body, lumbar spine, Ward's triangle, and proximal femur in postmenopausal women.

High impact interventions for school children included relatively brief additions (10 minutes, 3 times per week) to the regular physical education program and consisted of a variety of exercises such as 2-footed jumps, tuck jumps, plyometric jumps and jumps off of boxes or steps. This resulted in greater changes in bone mineral content for intervention children than controls at several skeletal sites (Fuchs, Bauer & Snow, 2001; MacKelvie, McKay, Khan & Crocker, 2001; MacKelvie, Petit, Khan, Beck, & McKay, 2004).

Variable exercise programs that include diverse exercise modes and sports positively influence bone health. Morris, Naughton, Gibbs, Carlson and Wark (1997) designed a ten-month exercise program for girls aged 9 to 10 for 30 minutes, three times a week during the 10-month school year. The intervention group participated in high impact aerobics, soccer, step aerobics, dancing, skipping, ball games, and a weight training circuit that used dumbbells, elastic bands and the girls' body weight in exercises that stressed the major muscle groups. Although much of the bone gain was due to growth, the exercise group had significantly greater increases of the total body, femoral neck, proximal femur and lumbar spine bone mineral content than non-exercising controls. Welsh and Rutherford (1996) defined their exercise intervention as high impact, yet only seven minutes of the session included jumping, skipping, side stepping or marching. Stepping and marching are most likely low impact (Johnson, Rupp, Berry & Rupp, 1992). The rest of the program consisted of standing muscular endurance exercises and floor exercises for the abdomen and back. At the end of this 12-month intervention, proximal femur BMD in men and women over the age of 50 had increased.

Weight training is also effective at improving bone density in various populations. Six months of resistance training using variable resistance machines, dumbbells, and floor exercises aimed at all major muscle groups benefited young women and men ages 20-29 years as well as older men and women aged 65-74 years. Both groups significantly increased BMD at three measured sites of the femur (Ryan et al. 2004). Stengel et al., (2005) randomized two groups of postmenopausal women into an exercise program with three identical components; a weight lifting session, gymnastics session, and home training session. The gymnastics session included balance, flexibility, and strength exercises (without weights), and the home session included rope jumping, stretching, and isometric exercises. The weight lifting session, carried out on variable resistance machines at a fitness center, was also identical for both groups except that the strength training group was coached to perform both the concentric and eccentric phases of the contractions in four seconds, while the power training group was coached to perform the concentric contraction as quickly as possible and the eccentric contraction in four seconds. After 12 months the power training group had maintained BMD at the lumbar spine and total hip. Although the results were not significant, the strength training group lost BMD at both sites; thus the researchers concluded that the quick, explosive contraction employed by the power training group was more effective at maintaining BMD in postmenopausal women.

Borer et al. (2007), conducted a detailed study of walking intensity and its effects on

BMD. The intervention group of postmenopausal women who exercised at high intensity (defined as walking speed of 6.14 km/h and at least 82.3% of their age-specific heart rate maximum), increased BMD of their legs and total skeleton that approached statistical significance. The researchers concluded that fast walking is osteogenic, or of sufficient strain to benefit bone, at a peak vertical force of 872.3N or greater which corresponds to a force of approximately 1.22 times body weight.

In summary, there are many modes and combinations of exercise that appear to be beneficial to bone health. It is not unreasonable to assume that a hatha yoga program could be an effective exercise regimen for promoting bone health since its asanas generate force through muscle contraction and weight bearing, in similar fashion to many of the exercises included in the aforementioned experimental designs.

Ground Reaction Force by Exercise Type

Table 2 contains results from several studies that identify either a range of or average peak GRF normalized to subjects' body weights that were measured in a variety of exercises. Grove and Londeree (1992) measured a variety of movements used in high and low impact aerobic exercise programs. Peak forces were measured for barefoot subjects who performed intermittent and continuous jumps (Kato & Bassey, 2002). Aerobics instructors performed routines at varying step bench heights and peak vertical GRF was measured at time of foot contact with the bench (Maybury & Waterfield, 1997). Johnson et al., (1992) identified ground reaction forces of 1.13 times body weight, 1.74 times body weight, and 1.27 times body weight for walking, low impact marching, and pushing off of the aerobic step, respectively, and Rousanoglou and Boudolos (2005) quantified GRF of various exercises using both male and female aerobics instructors. All of this normative data is useful in categorizing different types of exercise as high or low impact and in providing a reference for comparison to the GRF generated by hatha yoga asanas.

Chapter 3

Methods

Subjects

Ten women and 10 men will be recruited from local yoga studios and fitness centers. These subjects will have either three years experience practicing hatha yoga or will be yoga instructors. They will be selected because of their expertise in executing the yoga postures correctly and consistently. Both men and women will be invited to participate since this reflects the population that practices yoga. In addition, gender differences in GRF were not significant in a study of adolescent males and females who all differed in exercise background and ability and from whom GRF data were obtained for jumping (McNair & Prapavessis, 1999).

The study will be approved by the local IRB and each subject will sign an approved informed consent form prior to data collection. A practice session will be held with each participant prior to the data collection session in order to ensure uniformity of execution. Each subject will be compensated for his or her time.

Dependent Variables

The dependent variables measured will be:

1. The peak vertical GRF and average vertical GRF for each of the 28 hatha yoga exercises for each subject.
2. The peak resultant force and average resultant force for each of the 28 hatha yoga exercises for each subject.

Instrumentation

An AMTI strain-gauge force plate with dimensions 40 cm x 60 cm, will be used to measure GRF data generated during a typical hatha yoga practice. Signals will be sampled at 1000 Hz and converted from analog to digital using Vicon Nexus software that interfaces with the force plate. Ground reaction force data will be expressed in Newtons. Mathlab software will then be used to process the reaction force data into average values for each asana.

Procedure

Weight in kilograms and height in centimeters will be obtained for each subject using an electronic scale and a stadiometer, respectively. Body weight in kilograms will be multiplied by 9.81 to convert it to Newtons. Each subject will warm up using the force plate for approximately five minutes. A short hatha yoga sequence incorporating 28 commonly used asanas will be performed six times by each subject (see Appendix). Ground reaction forces will be measured three times with the subject positioned so that the upper limbs contact the force plate during the sequence followed by three times with the lower limbs in contact with the force plate during the sequence. The perimeter of the force plate will be drawn onto a sticky yoga mat which will be placed on the floor over the plate. This will keep the subject oriented to the plate area for proper hand and foot placement. The subject will be verbally cued to perform each successive asana and will have five seconds to complete it. This five-second time period will provide a few moments of stabilization between the postures. During the five-second interval, GRF data will be collected by the force plate. Each sequence will last approximately four minutes. Subjects will be permitted to rest as needed between each repetition of the sequence. The total time for each subject's session is expected to be approximately 40 minutes.

Statistical Analysis

Peak vertical GRF, average vertical GRF, peak resultant GRF, and average resultant GRF values will be calculated for all asanas in each subject's six trials. These values will be divided by the subject's body weight in Newtons in order to express the GRF as a ratio to body weight. A range for the entire hatha yoga sequence for each subject will then be identified as well as a range across all subjects. In summary, analysis will consist of calculating mean values and standard deviations for the GRF data and in establishing a range of forces as a ratio to body weight for the hatha yoga sequence as a whole.

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