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Biomechanical Evaluation of Postures Assumed
When Harvesting from Bush Crops

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Abstract

The objectives of this research were to explore the changes in the low back biomechanical responses during a harvesting task as a function of different harvesting techniques/postures and to explore the effects of an ergonomic intervention designed to reduce the low back stress during this work activity. Nine participants performed a series of simulated harvesting activities in a laboratory setting using four different harvesting techniques: full kneeling posture, squatting posture, stooping posture and kneeling on a knee support device (the intervention). As they performed these tasks the activity of muscles of the torso and thighs were captured using electromyography and trunk kinematics were captured using the lumbar motion monitor and a magnetic field-based motion tracking system. The results showed that (1) three postures - knee support, squatting, and stooping - required high flexion of low back (more than 60°) and (2) squatting and stooping postures showed significantly higher passive tissue moment compared with two kneeling postures. The results also indicate that the beneficial aspects of the knee support intervention appear to be outweighed by reduced productivity and the high degree of trunk flexion and that the current strategy used by these workers of alternating between the various harvesting postures may be the best strategy available.

Relevance to Industry: Understanding how changes in harvesting technique affect lumbar biomechanics can help ergonomists design effective interventions for the prevention of back injury in farmworkers.

Keywords: harvesting postures, ergonomic intervention, EMG

INTRODUCTION

There is considerable evidence that shows that workers in the agriculture industry are at high risk for developing work-related musculoskeletal disorders (e.g. Osorio et al., 1998; Xiang et al., 1999). In crop farming, while the specific regions of the body that are affected can vary somewhat depending on the specific crops being farmed, disorders of the low back and lower extremities appear to be endemic to the occupation. A review paper developed by Walker-Bone and Palmer (2002) provided evidence from the scientific literature that there was a higher risk of hip osteoarthritis, knee osteoarthritis and low back pain in farmers than in other occupations with lower physical demands.

One of the farmwork tasks that challenges the low back and lower extremities of these workers is crop harvesting. The specific biomechanical stressors vary considerably depending on the particular crop to be harvested. Tree crops (apples, oranges, pears, etc.) require overhead reaches, awkward postures of the low back when picking, high low back loads when carrying buckets of produce, ascending and descending ladders, downward pressure on the shoulder and upper back when using a harvesting bag (Conlan et al., 1995; Fulmer et al., 2002). Ground crops (cucumbers, sweet potatoes, melons, etc.) require static stooped postures of the low back, kneeling postures and heavy lifting from ground level when lifting the buckets of produce. Bush and vine crops (peppers, tomatoes, grapes, etc.) require static stooped postures, lateral bending of the torso, kneeling postures, squatting postures and heavy lifting of the buckets of produce from ground level (Myers et al., 2001).

Regardless of the crops being harvested, the development of ergonomic solutions for these tasks is made difficult by the dynamic and natural environment in which this work is performed.

There have been a number of ergonomic interventions developed to reduce the biomechanical loading during harvesting tasks. In a study that focused on the harvesting of apples, Earle-Richardson et al. (2005) describe modifications that were made to the harnessing system that secured the harvesting bucket to the worker. These modifications included wider straps along the shoulders to better distribute the compression load in the shoulder region and a waist belt to transmit more of the weight of the load directly to the hips thereby reducing the loading on the low back. In a study that focused on the harvesting of wild blueberries, Estill and Tanaka (1998) described a roller rake intervention that reduced the need for stooped postures when harvesting the low lying wild blueberries. Okano et al. (2001) describe a high bench system for raising single truss tomato plants to a more workable height that reduces the height of the tomato plant and its fruit and thereby eliminates the awkward postures of the torso during harvest. Finally Kato et al. (2006) describe the differences in posture and loading of the low back while working with winegrapes on different types of trellis systems. It is often difficult to translate ergonomic intervention solutions across crops, not only because of the differences in the location of the produce to be harvested (overhead, ground level, knee level, etc.) but also because of difference in the sensitivity of the produce (e.g. hardiness of the wild blueberries vs. the fragility of the tomato and grape) and differences in the mobility requirements of the worker during harvest.

The development of an ergonomic intervention for the task of harvesting of peppers presents an interesting challenge from a number of perspectives. First, the location of ripe peppers can vary from ground level up to approximately waist height and can be up to a meter away (horizontal distance) from the rows in which the worker is standing. Second, peppers ripen at different times meaning that all peppers are not harvested at once and the worker must evaluate each to identify the whether it is ready for harvest. Third, the volume of peppers from an individual plant is such that the worker needs to move frequently from plant to plant during the harvesting task. As part of the current research, a knee support device was designed and developed. The objectives of this research were to explore the changes in the low back biomechanical responses as a function of different harvesting techniques/postures and to explore the effects of an ergonomic intervention designed to reduce the low back stress during this work activity.

METHODS

Brief Overview of Study

There were two phases of experimentation in this study: a static phase and a dynamic phase. The first phase sought to better understand how the muscles of the low back and lower extremities work to maintain the various harvesting postures. This was accomplished by having the participants assume various static harvesting postures and sampling the relevant muscles with electromyography as well as obtaining a measure of lumbar curvature. In the second phase of the experiment participants performed a simulated harvesting task while the three-dimensional postures and motions of the torso were captured and productivity was assessed. In each of these experiments participants performed these activities while assuming four different harvesting postures: stooping, squatting, full kneeling and kneeling on a knee support devices.

Participants

There were nine participants in this study. The age, stature and whole body mass (and standard deviation) of this study population were 27.2 yr (4.2), 176.1 cm (3.4), and 73.6 kg (9.4). All subjects reported that they had no history of low back injury and none were currently experiencing low back pain. The study was approved by the North Carolina State University Institutional Review Board for the Use of Human Subjects in Research and all participants provided written informed consent before participation.

Apparatus

The experimental setup was designed to create a pepper harvesting task in a laboratory setting (Figure 1). Two frames were built and placed approximately 4m apart. Four lines were strung between these two frames. The lines were strung at heights of 38 cm and 68 cm off of the ground, and separated horizontally by a distance of 50 cm. The horizontal and vertical distances of experimental setup were designed to mimic a sample of locations of peppers in a commercial pepper plant. One hundred clips (common clothespins) were placed every 15cm on each of these four lines (25 on each line). While it is clear that this approach to experimental apparatus design limits the generalizability of results to realistic harvesting scenarios, it allows for an evaluation of the impact of harvesting height and harvesting depth that would not be available if these “peppers” were placed randomly in this three-dimensional space.

Insert Figure 1 about here

The ergonomic intervention tested in this study was a wearable knee support device (Figure 2). The goals of these knee supports are to lower the height of torso and upper limbs and relieve stress on the ankles and knees. By lowering the height of the center of mass of the torso, the aim is to reduce trunk flexion necessary to reach the fruit throughout the harvesting process. The structure of the knee supports also provides a more natural ankle posture (no extreme flexion or extension) and less contact stress on knees by distributing point stress on knees to the whole surface of the shins. The supports (one for each leg) are constructed from high density foam commonly used in the shipping industry. The foam blocks measured approximately 36cm by 20cm by 20cm. The blocks are shaped to comfortably cradle the knee and shin while worn and further comfort are provided through a low density foam and cloth covering. The weight of knee supports is 0.7 kg per support. The knee supports are strapped to the individual along the upper and lower calf and allows the wearer to walk around while wearing the supports. When kneeling on the supports, the subject’s knees are elevated off of the ground by approximately 16 cm.

Insert Figure 2 about here

The first part of the experiment consisted of a series of static trials that focused on muscle activation profiles and static low back posture. In this phase the subjects were first fitted with 10 pairs of surface Ag-AgCl electrodes (Model E22x, In-Vivo Metric) that were used to collect the electromyographic (EMG) muscle activity of the sampled muscles. These EMG data were collected at a rate of 1024 Hz. The sampled muscles were the bilateral: erector spinae (ES), multifidus (MF), rectus abdominis (RA), rectus femoris (RF), and biceps femoris (BF). These muscles were chosen as they would have a direct impact on spinal loading (ES, MF, RA) or hip/knee biomechanics (RF, BF) and are hypothesized to be affected by harvesting posture. The sampling locations for these muscles are as follows: (1) erector spinae: 3.5 cm from the vertebral midline at L2 level, (2) multifidus: 1.5 cm from the vertebral midline at L5 level, (3) rectus abdominis: 5 cm above the umbilicus and 3 cm lateral to the midline, (4) rectus femoris: 10 cm above the knee joint cleft, and (5) biceps femoris: 12 cm above the knee joint cleft. To capture the posture of the lumbar spine, participants were also fitted with sensors from a magnetic field-based motion tracking system (Motion Star, Ascension Technology Corp. Burlington, VT). Two sensors were placed over the spine, one at the L1 level and the other at the S1 level and these sensors provided measures of angle in the sagittal plane. These data were then used to estimate the lumbar flexion angle (Dolan et al., 1993). These data were collected at 100Hz.

During the dynamic trials, the lumbar motion monitor (LMM) was used to quantify the three-dimensional postures of the torso necessary to perform the harvesting activity. The LMM is essentially an exoskeleton that measures the angular position of the torso in the three cardinal planes of human motion: sagittal plane, coronal plane and transverse plane at a rate of 60 Hz (Marras et al., 1992). Finally, a stopwatch was used to quantify the task completion times during the dynamic harvesting task.

Experimental Design

In the static phase of the experiment there were three independent variables: horizontal position (HORIZ), vertical position (VERT) and harvesting posture (POST). There were two levels of HORIZ: "near" and "far", referring to the two different horizontal locations of the ropes. There were two levels of VERT: "low" and "high", referring to the two different vertical positions of the ropes. There were four levels of POST: (1) full kneeling (FK) (kneeling on the ground with two knees), (2) knee supports (KS) (kneeling on the knee support interventions), (3) full squatting (SQ) (fully flexing the knees), and (4) stooping (ST) (flexing forward with the torso and straight knees). In the dynamic trials the only independent variable was POST because the subjects performed the harvesting task across all four spatial locations during an individual trial.

The dependent variables during the static trials included both measures of muscle activation and an estimate of the moment provided by the passive tissues of the low back. The normalized (to maximum) EMG of each pair of muscles was averaged to provide an assessment of the intensity of activation of these muscles groups. These included the averaged, normalized values of the erector spinae (ES), multifidus (MF), rectus abdominis (RA), rectus femoris (RF) and biceps femoris (BF).

The moment provided by the passive mechanism was estimated using the lumbar angle data provided by the L1 and S1 motion sensors and the method employed by Dolan et al. (1993) (see below for calculation method). In the dynamic trials the dependent variables were measures of trunk posture: the average sagittal angle of the torso, the average absolute angular deviation (from neutral) in the coronal plane and average absolute angular deviation (from neutral) in the transverse plane. Productivity was also assessed by documenting the number of seconds it took to harvest all 100 pins from the ropes.

Experimental Procedures

The first part of the experiment consisted of a series of static, posture maintenance trials. First, subjects were fitted with the ten pairs of surface electrodes and the motion sensors. The subjects completed a series of isometric maximum voluntary contractions using the static resistance provided by two different dynamometer systems. For the muscles of the thigh, a Kin/Com 125E system was used to provide the static resistance in both knee flexion and knee extension as the knee was held at about 90°. For the muscles of the torso, a lumbar dynamometer (Marras and Mirka, 1989) was used to provide the static resistance (both trunk flexion and trunk extension) as the participants assumed a 40 degree trunk flexed posture. Two minutes of rest were provided between maximum exertions.

After completing the maximum exertion trials, the subjects then were asked to move to the harvesting area (Figure 1). Once there, they were asked to stand in an upright posture and then to bend forward to a full trunk flexion posture. Data from the L1 and S1 motion sensors were collected to establish the participant's full sagittal plane range of motion. Following these normalization exertions, the static harvesting tasks began. The trials consisted of the subject reaching both hands to a pin while assuming the designated harvesting posture (stoop, squat, kneel or kneel on support) and holding that posture for five seconds while data (EMG and lumbar posture) were collected. There was a break of about 15 seconds between consecutive data collection periods. Complete randomization of the presentation order of the trials was not achieved in that once the participant was in one harvesting posture they completed all four of the spatial locations (the presentation order of these 2x2 levels was randomized). Concerns related to subject fatigue and the amount of time that it took to put on and remove the knee support devices led to this experimental design choice. There were two replications of each trial. After completion of these trials the surface electrodes and the motion sensors were removed.

Upon completion of the static trials the participants performed the dynamic harvesting trials. The lumbar motion monitor was placed on the back of the subject and a set of normalization trials were conducted wherein the subject assumed an upright posture and then a 90 degree trunk flexion while the data from the LMM were collected. The experimental trials consisted of the subject "harvesting" all 100 pins from the ropes as quickly as they could. They performed this task in each of the four levels harvesting posture (stoop, squat, full kneel or knee support) and there were two replications of each condition and the presentation order was completely randomized. There was a break of about two minutes between trials. After completing all eight trials the LMM was removed and the subject was free to leave.

Data Processing

The EMG data collected during the static exertions were filtered (high-pass 10 Hz, low-pass 500 Hz, notch filtering employed as needed to address 60 Hz and noise generated by the magnetic motion tacking system), rectified and averaged across all five seconds that the data were collected. These data were then normalized to the muscle-specific maximum value and the bilateral pairs for each muscle were averaged. For a number of the subjects problems were encountered with collecting the EMG activity for the RA muscles in the flexed postures (subcutaneous tissue challenges related to orientation of electrodes, etc.) Therefore, unfortunately, data from the rectus abdominis are not considered in the results of this study.

The sagittal plane angle data collected from the motion tracking sensors placed at L1 and S1 were used to quantify the total curvature of the lumbar spine during the static experimental trials. First, the difference between the sagittal angle of the sensors at L1 and S1 were found for each trial (experimental trials as well as the upright and full flexion normalization trials) (Equation 1). Next, the values of the lumbar curvature (LC) during the upright and full flexion posture were used to create the full range of trunk flexion. Using Equation 2, the percentage of this range of flexion for each individual static harvesting posture could be calculated. This percentage flexion value was then used in Equation 3 to calculate the passive tissue moment (Dolan et al., 1993).

Lumbar curvature (LC in deg) = $SagAng_{L1}$ - $SagAng_{S1}$ (1)

$$\text{Percentage Flexion}_i\ (\text{PF}_i \text{ in } \%) = \frac{[LC_i - LC_{(uprihgt)}]}{[LC_{(fullflexion)} - LC_{(upright)}]} \times 100 \quad (2)$$

$$\text{Passive tissue moment (in Nm)} = 7.97 \times 10^{-5} \times PF^3 + 12.9 \quad (3)$$

The trunk kinematic data collected from the LMM during the dynamic trials were used to compute the dependent measures. The average sagittal angle was simply the average of all sagittal angles collected during the harvesting process. The average side bend angle and the average rotational position were the average of the absolute value of the deviation of these values from neutral.

Statistical Analysis

Due to the multivariate nature of the data collected in this study, both MANOVA and univariate ANOVA techniques were used. Prior to conducting these formal analyses, the assumptions of the ANOVA technique (normality of residuals, homogeneity of variances and independence of observations) were evaluated using the graphical approach advocated by Montgomery (2001). The normalized EMG data and the passive moment measures violated the homogeneity of variance assumption and a natural log transformation was performed on these data. Subsequent analyses showed this transformation to be effective. Multivariate analyses of variance (MANOVA, $p < 0.05$ for Wilks' Lambda statistic) were conducted, and univariate ANOVA ($p < 0.05$ for F statistic) were conducted for those independent variables (and interactions) that were found to be significant in the MANOVA.

RESULTS

The results of the MANOVA for the data collected in the static trials showed a significant effect for all of the three independent variables and the interaction between POST and HORIZ (Table 1.) The subsequent univariate ANOVA showed that the response of the erector spinae and the multifidus followed a consistent trend. For both of these muscles (and the passive tissue moment) the significant POST*HORIZ interaction was the result of a significant decrease in the response under the full kneel, knee support and squat condition as the horizontal location went from far to near, while there was no response in these variables for the stoop condition (Figure 3.) The response of these measures to the different levels of POST showed the interplay between the active and passive tissues of the low back (Figures 4 and 5). The stoop posture generated high levels of passive tissue moment and low levels of erector spinae and multifidus muscle activity. The full kneel (FK) and knee support (KS) conditions, conversely showed higher levels of muscle activation and less moment from the passive tissues. The results can be attributed to the flexion-relaxation phenomenon of the erector spinae and multifidus muscles that have been shown to be initiated at 60 degrees of trunk flexion (Shin et al., 2004). Given the differences in the moment arms of the passive vs. the active tissues, these differences have important implications for spinal loading.

Insert Table 1 and Figures 3-5 about here

The results of the MANOVA for the data collected in the dynamic trials yielded a significant effect for POST and univariate ANOVA (Table 2) revealed an effect of POST on the average sagittal angle, the average coronal angle (Figure 6) and the productivity (Figure 7). The full kneeling (FK) posture generated an average sagittal angle that was significantly lower than the other three postures, and the average sagittal angle of the stooping posture was significantly higher than the other three postures. In terms of the coronal angle, the full kneeling posture and the knee support posture generated statistically higher levels of coronal angle than did the squat and stoop postures. The results of the productivity assessment showed that the knee support condition did generate a significant increase in the time to complete the task.

Insert Table 2 and Figures 6 and 7 about here

DISCUSSION

During our field studies of farm workers performing pepper harvesting tasks, we noted a variety of torso and lower extremity postures that were used to perform the task - from kneeling on the ground, to sitting on their heels in a full squatting posture, to bending only at the waist in a stooped posture. We also observed that the workers often switched from posture to posture to relieve the fatigue that was developing in the muscles used to hold these postures. A more formal analysis of these activities revealed that the posture that generated the lowest net external moment was the full kneeling posture. When asked why this particular posture was not used more, the workers responded that it took a great deal of effort to arise from a full kneeling posture and this fatigued their thigh muscles and slowed them down in their work. This led us to the development of a knee support device (Figure 2) that would have the benefits of lowering the center of mass of the torso to a height that would reduce the required bending of the torso, but would also avoid the negative aspects of the full kneeling posture that were so limiting. This study was designed to provide quantitative biomechanical data about the effects of this intervention as well as the three postures currently used by pepper harvesters.

The data from the static and dynamic trials provide a different, but complimentary, perspective on the effects of the different harvesting postures. The data collected during the static trials showed a clear tradeoff between the active and the passive tissues of the low back among the four postures evaluated in this study. The stooping and squatting postures showed significantly lower muscle activities of the erector spinae and multifidus muscles as compared to the full kneeling and the knee support positions. In the stooping posture this reduced level of extensor muscle activity came at the cost of an increase in the moments generated by the passive tissues of the low back. The average passive tissue moment of the stooping posture (83 Nm) was more than double the moment of the squatting (38 Nm) and knee support (32 Nm) postures, and nearly five times as high as the full kneeling posture (17 Nm). In addition, the trunk kinematics data collected during the dynamic tasks supported the findings of the higher moments by showing the higher flexion nature of the stooping posture (81°) throughout the dynamic trials. Solomonow et al. (2002) demonstrated that occupational and sports activities which require higher lumbar flexion and prolonged static lumbar flexion can result in the development of spasms and sprains because of the constant stress applied to the viscoelastic structures. The generation of passive tissue moments in the current study would indicate some involvement of these tissues in posture maintenance and may begin the processes described by Solomonow and colleagues.

When comparing the knee support intervention with the other three postures one must consider not only the data collected in this study, but also the characteristics of the work task to fully understand its potential benefits and drawbacks. Comparing the knee support device with the full kneeling posture, there was no significant difference in the activation of either the erector spinae or multifidus but there was a significant increase in the average sagittal angle and passive tissue moment. This would indicate that the additional vertical displacement of the center of mass of the torso (~16cm) required additional trunk flexion and the moments generated were resisted by the passive tissues of the low back. Comparing the knee support to the squat posture, there was a significantly lower muscle activity level (both erector spinae and multifidus) in the squatting posture and a slightly greater passive tissue moment. These two postures had similar trunk flexion angles throughout the dynamic trials (knee support: 60° vs. squatting: 63°). These results might lead one to conclude that the squat posture is superior, however, the squatting posture has a couple of intrinsic drawbacks for extended tasks like agricultural produce harvesting: tension on internal knee structures and poor circulation in the lower extremities, both of which have been shown to cause fatigue and pain (Basmajian, 1978). Finally a comparison of the knee support device with the stoop posture shows that the large sagittal angle (and thereby the high external moment created by the mass of the torso moment) and the high levels of passive tissue loading of the stoop posture makes this a very unappealing option for this task. In conclusion, our results indicate that the potentially beneficial aspects of the knee support intervention appear to be outweighed by reduced productivity and the high degree of trunk flexion (creating greater moments and passive tissue loading) and that the current strategy of alternating between the various harvesting postures may be the best strategy available.

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Table 1. MANOVA and ANOVA results for normalized EMG and passive moment

	MANOVA	ES	MF	RF	BF	Passive
POST	***	**	***		***	**
HORIZ	***	***	***	*	***	***
VERT	*	**	**			**
HORIZ*VERT						
POST*HORIZ	**	**	**		*	**
POST*VERT						

Note: ES (erector spinae), MF(multifidus), RF (rectus femoris), and BF (biceps femoris)

* (p<0.05), ** (p<0.01), and *** (p<0.001)

Table 2. MANOVA and ANOVA results for trunk posture and productivity data

	MANOVA	Sagittal	Coronal	Transverse	Productivity
POST	***	***	***		***

* (p<0.05), ** (p<0.01), and *** (p<0.001)

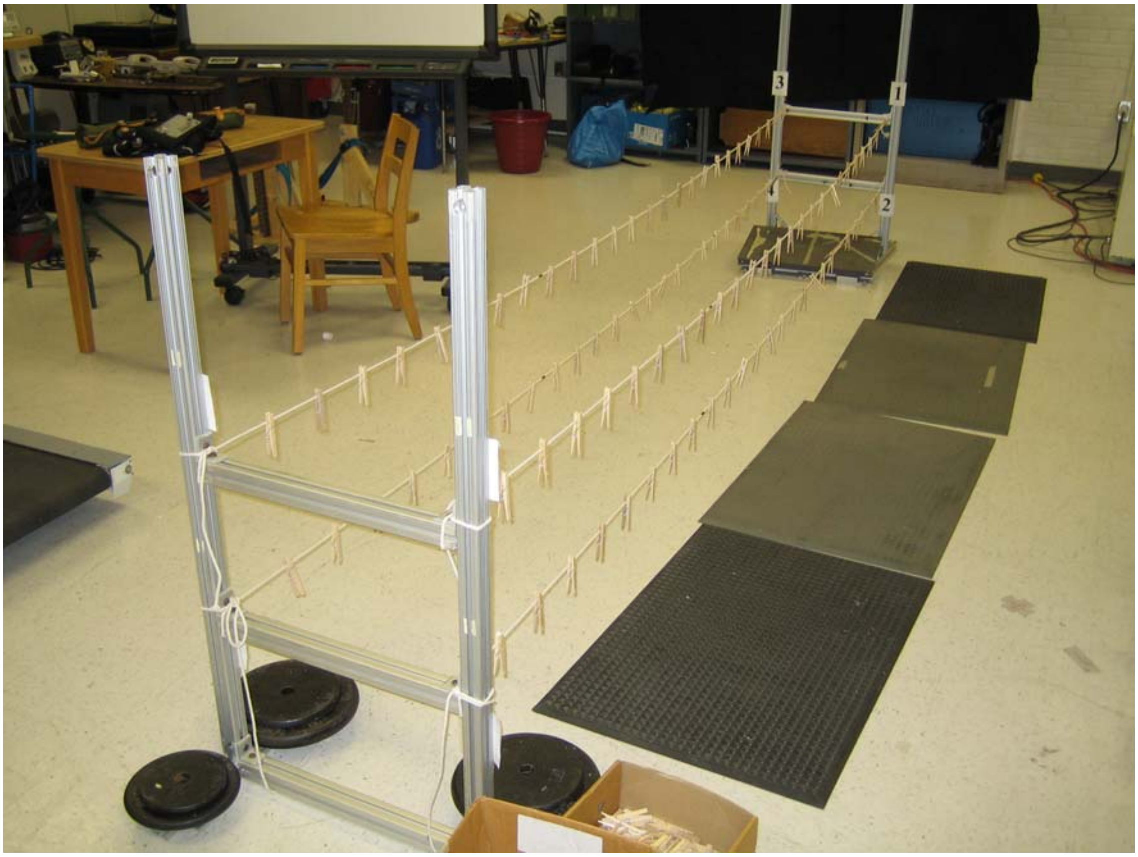

Figure 1. Harvesting simulation set up

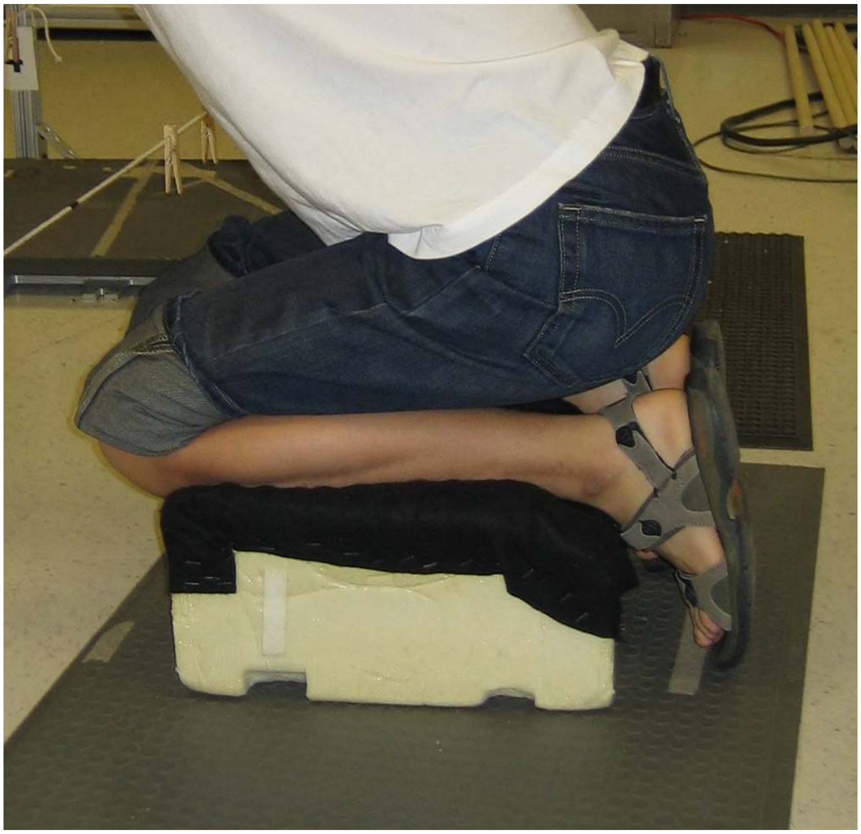

Figure 2. Side view of knee supports

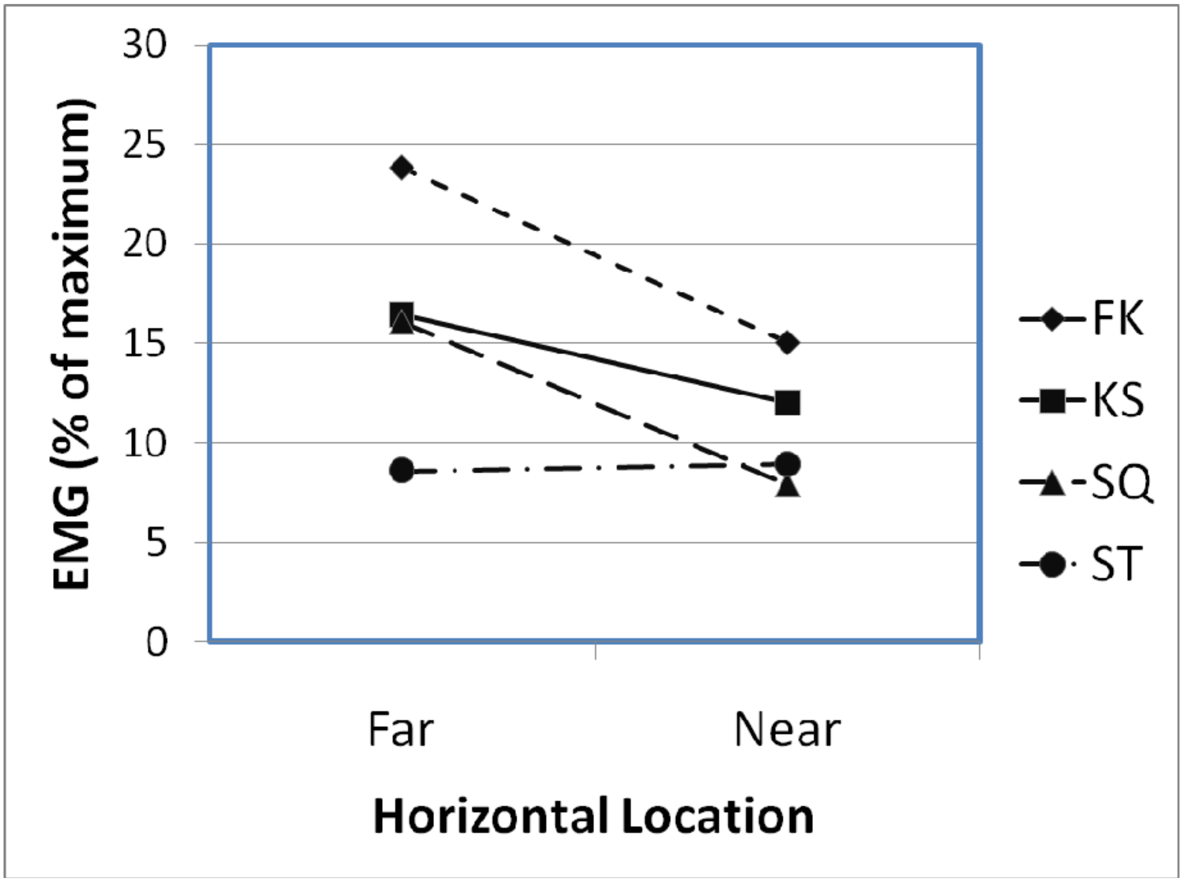

Figure 3. Interaction between harvesting posture (POST) and horizontal position (HORIZ) for the normalized EMG of the erector spinae. (FK - Full Kneel, KS – Knee Support, SQ – Squat and ST – Stoop)

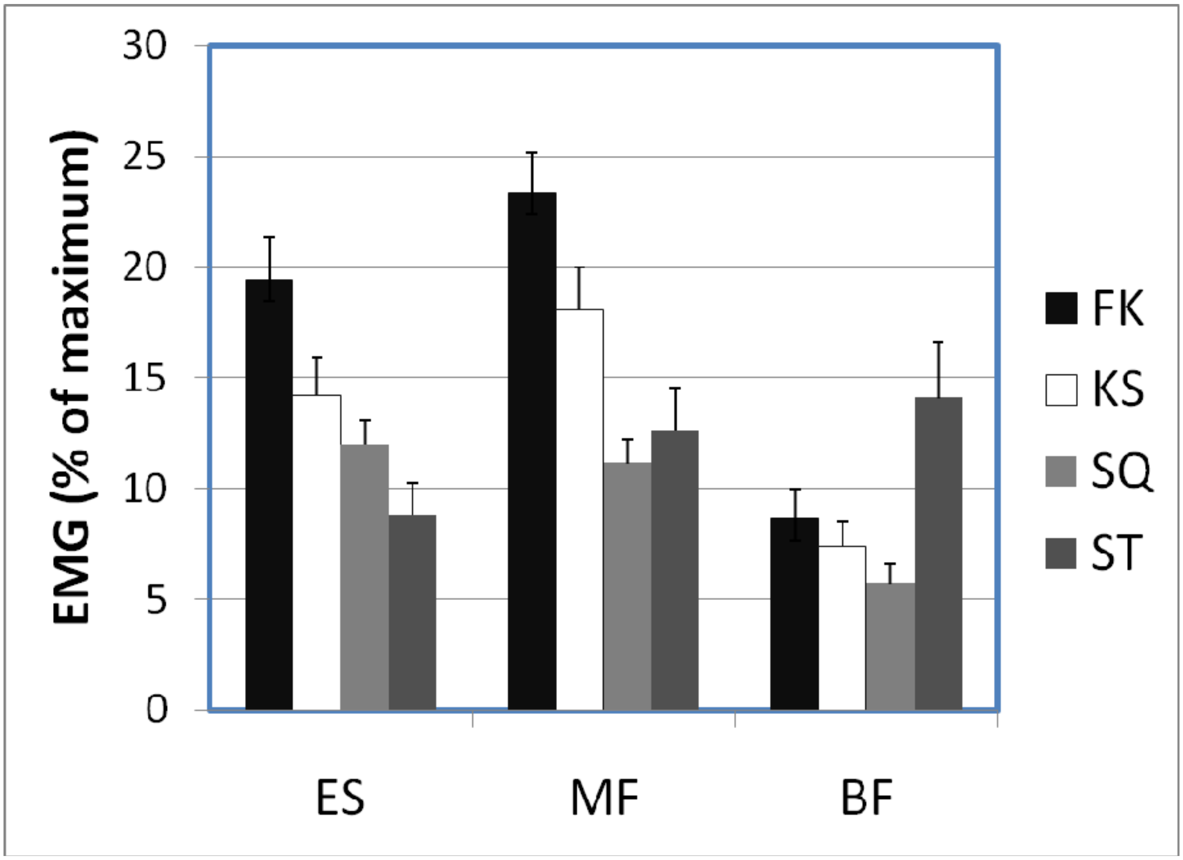

Figure 4. Effect of harvesting posture (POST) on the normalized EMG of the erector spinae (ES), multifidus (MF) and biceps femoris (BF) muscles (standard error bars shown).

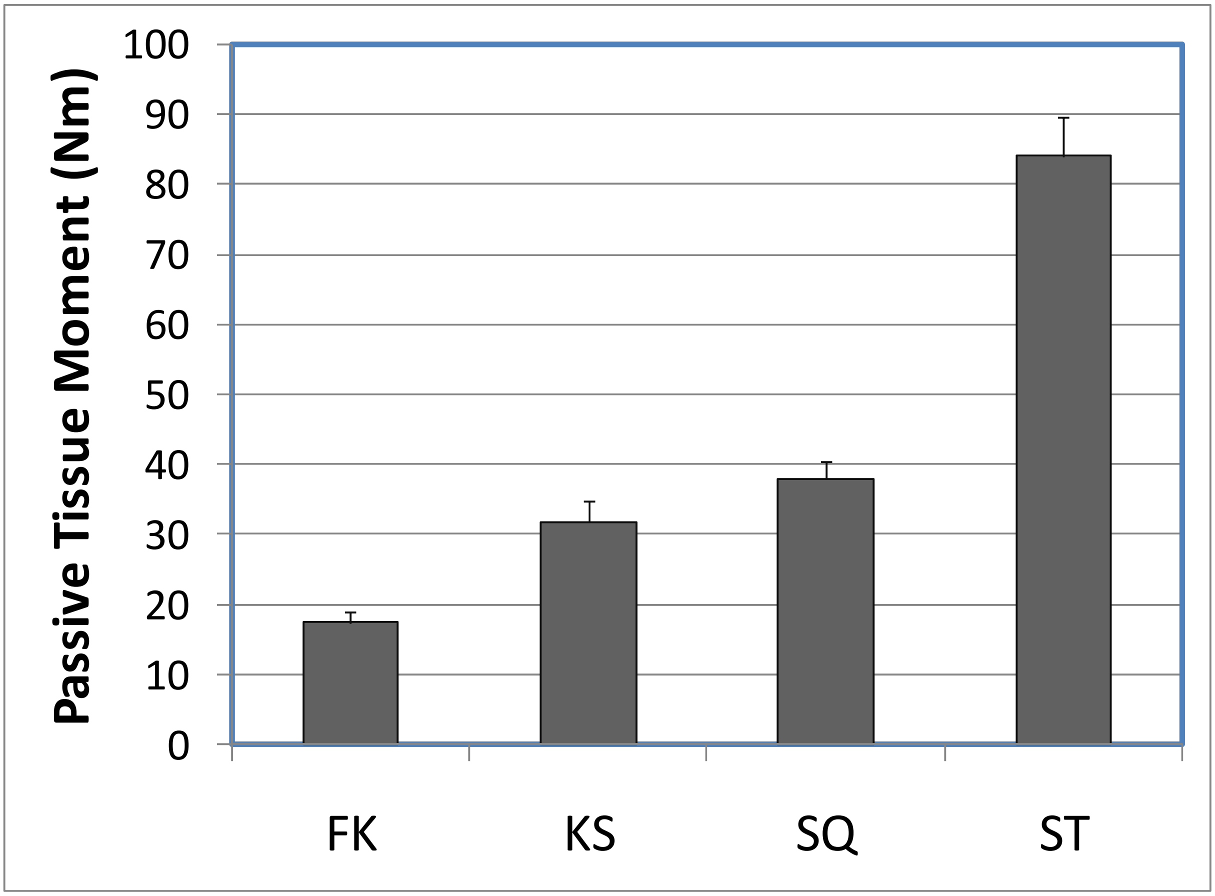

Figure 5. Effect of harvesting posture (POST) on the estimated passive tissue moments in the low back (standard error bars shown)

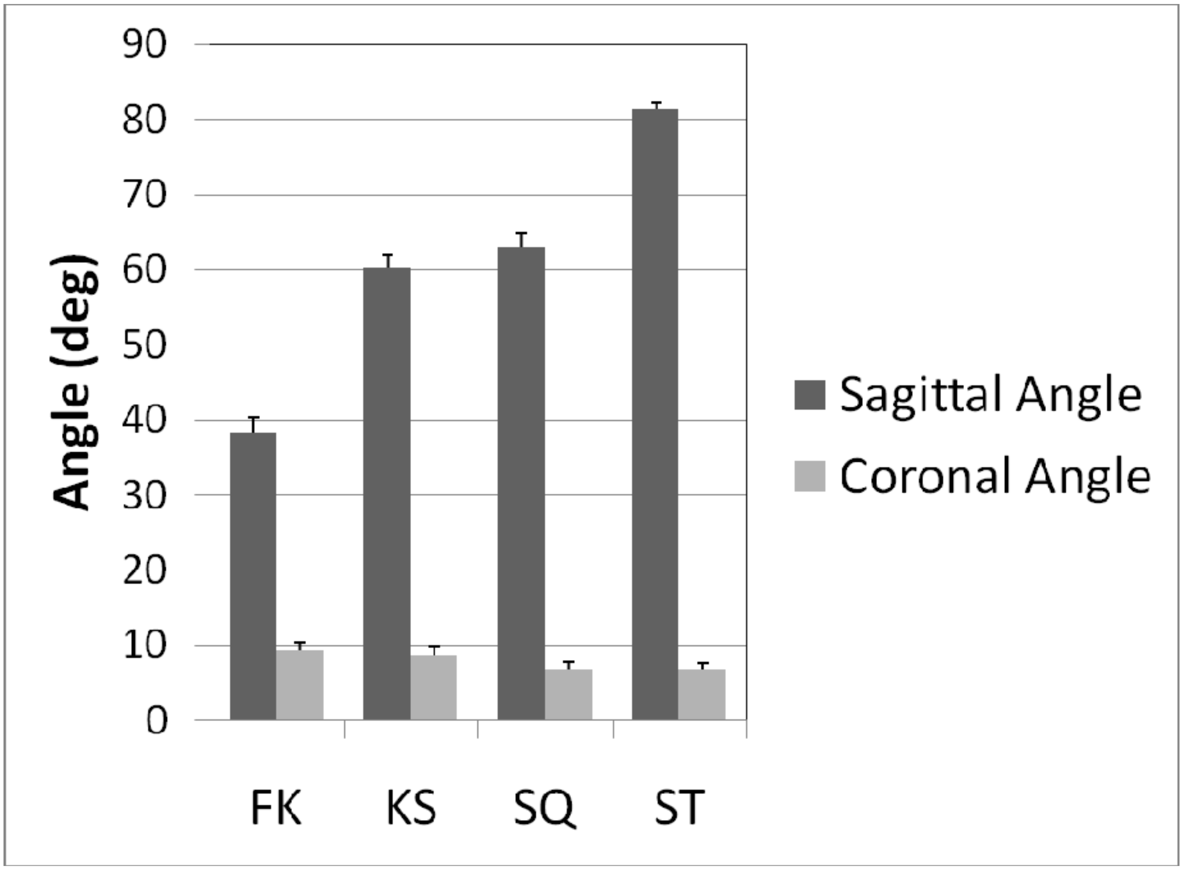

Figure 6. Effect of harvesting posture (POST) on the average sagittal angle and the average coronal angle of the low back (standard error bars shown)

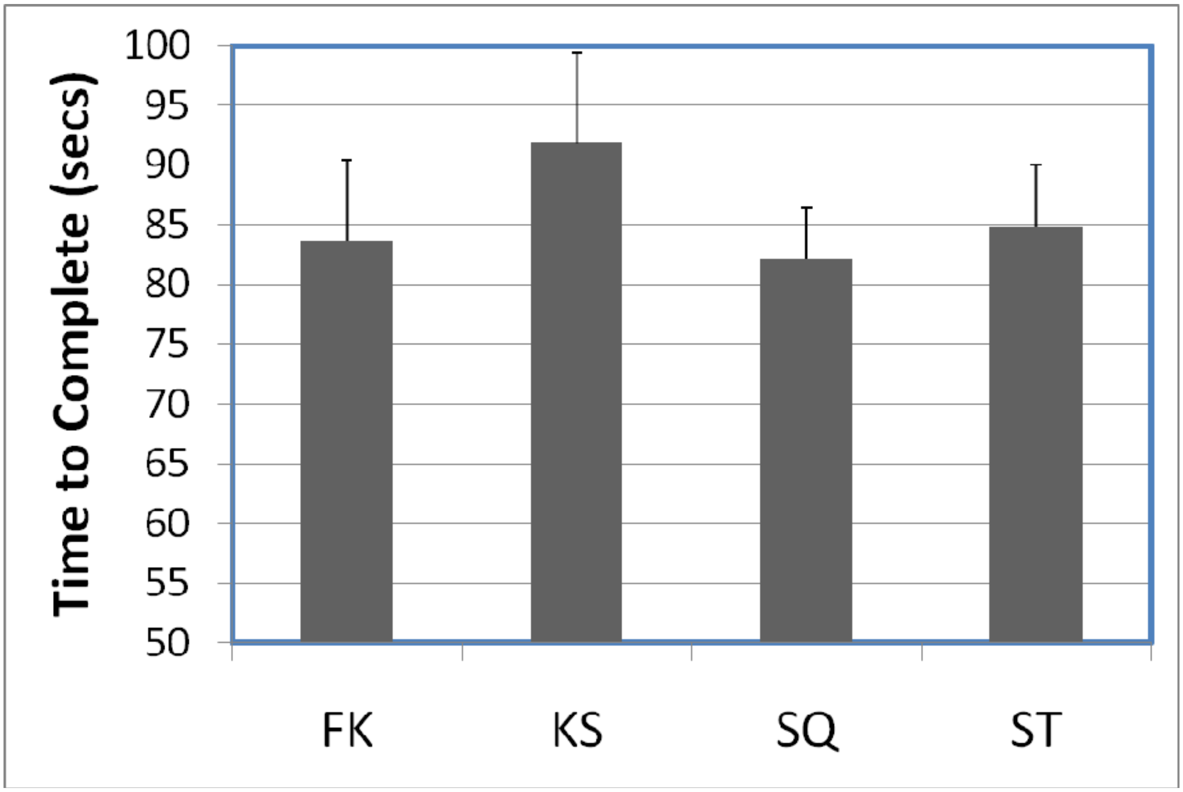

Figure 7 Effect of harvesting posture (POST) on the time to complete the harvesting task (standard error bars shown)