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Are knee savers and knee pads a viable intervention to reduce lower extremity musculoskeletal disorder risk in residential roofers?

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Abstract

One factor commonly associated with musculoskeletal disorder risk is extreme postures. To lessen this risk, individuals must be in an as neutral posture as possible while working. We analyzed how the inclusion of different combinations of two interventions—knee pads and knee savers—can alter lower extremity kinematics during deep or near full flexion kneeling occurs while on different sloped surfaces. Nine male subjects were requested to keep a typical resting posture while kneeling on sloped roofing simulator. We observed that the introduction of a wearable third party device considerably altered lower extremity full flexion kneeling kinematics compared to level deep kneeling. This study provided a sound base for the use of third party devices to reduce musculoskeletal disorder risk on a sloped surface, however further testing with other musculoskeletal disorder risk factors is needed prior to conclusive recommendation.

Keywords

Musculoskeletal disorders; Sloped surface; Residential roofers

Introduction

Musculoskeletal disorders (MSDs) are a major problem in the construction sector. For example, there were 20,340 “sprains and strains” and 12,910 “soreness, pain” injuries representing approximately 44.6% of all construction injuries and illnesses clearly related to

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MSDs in 2014 (BLS, 2016a, b). While many different factors are considered to contribute to MSD risk, only a few can be tested biomechanically. One of the ergonomic factors that is generally accepted as a major contributor to increase MSD risks are postures that are awkward and/or sustained. Roofers—given all the training and experience—have the second highest incident rate of work-related MSDs among all construction sectors (BLS, 2013). This is most likely due to the unique work environment (sloped rooftops), and that roofers spend more than 75% of their working time in crawling, squatting, stooping, and kneeling posture (Wang et al., 2017; Wang et al., 2015). Thus it is advantageous to look for simple and helpful interventions that might alleviate some of the awkward postures encountered by roofers during their work day on a sloped surface.

Due to the nature of affixing coverings—shingles/tar paper/tiles/etc.—roofers are often required to be in awkward kneeling and stooping postures. Therefore most MSDs that are reported by roofers tend to be located in the lower back and lower extremities (Holmström and Engholm, 2003). The cumulative effects of these awkward postures, combined with repetitive motions, may not only lead to low back pain, but also can increase the musculoskeletal loading in the lower extremities; factors leading to the initiation and acceleration of osteoarthritis (Wang et al., 2017; Wang et al., 2015). When roofers are burdened with MSDs, they face work limitation, missed work, and/or reduced physical functioning, leading to premature departure from the workforce (Welch et al., 2009; Welch et al., 2008, 2010). Musculoskeletal disorders among roofers have been far from adequately studied, partially due to the lack of available technologies required for the measurement and evaluation of the MSD risk factors on the jobsite. While it might be difficult to change the nature of the roofing task, investigating interventions that already claim to lessen MSD risk on level surfaces and determine how they elicit a biomechanical change on a sloped surface is an excellent place to start. While numerous studies and protective wearable interventions exist to reduce musculoskeletal injury risk for construction workers, very few, if any, exist specifically for roofers.

Typically, the kneeling posture is associated with affixing a roof covering. Kneeling is an extreme posture that can increase the likelihoods of developing an MSD and has been connected with discomfort in the knee represented by with numbness and tingling in the lower legs (Chung et al., 2005; Reid et al., 2010). While kneeling has been extensively studied following arthroplasty (Abo-Alhol et al., 2014; Barnes et al., 2011; Hanson et al., 2007; Lee, 2014; Moynihan et al., 2010) and it is associated with other work environments such as mining, plumbing, carpentry, electrical work, floor and carpet laying (Gallagher et al., 2009; Jensen et al., 2010; Tennant et al., 2015), no information could be found regarding kneeling on a sloped surface, however some of the existing guidelines suggest using mechanical device during roofing and knee pad while kneeling (Spielholz et al., 2006).

There are two third party wearable devices tested in this study—knee pads and knee savers—one, knee pads, are commonly used by construction workers that requiring kneeling and the other, knee savers, does not. Knee pads (KP) are widely used by several different occupations that require kneeling during the working task. There are many different styles of KP (Pollard et al., 2011; Porter et al., 2010; Xu et al., 2017) and the design of the knee pads can modify the knee joint forces (Xu et al., 2017). These wearable devices do influence knee flexion (Pollard et al., 2011) and decrease pressure at the patellar tendon and tibial tubercle (Porter et al., 2010). Again, all of this testing was conducted on level surfaces.

Knee savers (KS) are a device that is placed on the posterior aspect of the shank and contacts the posterior aspect of the thigh during squatting. The device was primarily developed as an ergonomic aid to lessen the knee injury risk during deep flexion of the knee and has been extensively used by catchers in baseball and softball (Stone et al., 2017). Most of the knee saver studies used female athletes with and without an anterior cruciate ligament (ACL) injury (Stone et al., 2014a; Stone et al., 2017; Stone et al., 2014b). These studies did not find any significant change in lower extremity sagittal plane knee kinematics with and without the KS. Another study compared deep and shallow flexing baseball catchers and indicated that the use of KS will decrease knee flexion in deep flexing catchers, albeit not statistically significantly (Gray et al., 2015). On the surface, it might seem KS would not be a beneficial intervention for any work place environment which uses kneeling, however, there are several things to consider. First, catchers do not kneel, they squat, so the use of KS during deep or near full kneeling could decrease large extreme knee kinematics. Second, all tests were conducted on a level surface, therefore, when on a sloped surface, the KS may engage with the posterior aspect of the thigh more readily than on a level surface.

While KP and KS have been shown to be helpful with reducing knee injuries, all these studies were completed on level surfaces or with very specific tasks. Thus it is completely unknown if the benefits/advantages from these devices while on a level surface will translate onto a sloped working environment. It is, however, nearly impossible to create a ‘golden’ solution to the MSD issue because MSD injuries are dependent on the response of the individual worker—physical and psychological—to the demands of the job. Nevertheless, there is strong evidence that all occupational musculoskeletal injuries are biomechanical in nature (Kumar, 2001). Consequently, concerted efforts for specific jobs and work environments to identify their associated MSD risks are needed. To that end, the purpose of this study was to determine if a third-party wearable device—designed to reduce MSD risk, within other occupations and on level surfaces—is able to reduce MSD risk in a roofing environment. This will be done by measuring the joint kinematics of the individual without intervention, and with the aid of KP, KS or both during a roofing task on a sloped surface. It is hypothesized the addition of wearable devices will alter resting kneeling kinematics in individuals on a sloped surface.

Methods

Only one posture was tested in this study, subjects were requested to use an upright resting posture on the roofing simulator or different angles. Nine male subjects (height: 180.6±6.1cm, weight: 99.7±27.6kg, age: 26.1±5.6years)—with no roofing experience—participated in the study. All subjects were male, as 97% of roofers are male and were healthy without any musculoskeletal or neurological disorders—such as stroke, head trauma, neurological Parkinson’s disease, diabetic neuropathy, dementia, or visual impairment uncorrectable by lenses—which would influence the outcome of the study. The protocol was approved by the National Institute for Occupational Safety & Health’s (NIOSH) Institutional Review Board (IRB) and subjects read and completed informed consent.

Subjects came to the NIOSH biomechanics laboratory for one testing day and were outfitted with eighty- two (9mm diameter) retro-reflective motion capture markers (Figure 1). Kinematic data were collected using 14 MX Vicon cameras (Vicon Inc., Oxford, England) at a sample rate of 100Hz. Trajectory data were filtered in Visual 3D (C-Motion, Germantown, Maryland), using a 4^{th} order Butterworth filter with a 6Hz cut off.

All data were collected while the subjects were in a deep or full flexion static upright kneeling posture on a roof simulator (Figure 2). This posture was selected because it allowed interaction—of the posterior shank and thigh—with the knee saver intervention. This was essentially described as a ‘resting’ posture roofers would assume when not affixing shingles to a sloped roof surface. In an active working posture, the knee flexion decreased and the thigh did not contact the shank.

The roof simulator could be locked into three different (0^0, 15^0, and 30^0) angles (Figure 3) and subjects were outfitted with four different combinations of wearable devices—no wearable assist device (NO), knee pads only (KP), knee savers only (KS), and both knee pads and knee savers (BO)—resulting in 12 combinations (Figure 4).

Data were collected after the subject was set and comfortable in the deep kneeling posture. Five trials of five seconds in each of the 12 configurations were collected to determine how the wearable devices influenced kneeling kinematics while on a roof surface. Subjects were allowed no acclamation time on the sloped surface, and kinematic data were collected immediately after the subjects were comfortable in the kneeling posture. This was done to capture the kinematic change that occurs when individuals are first introduced to the various wearables.

Outcome measures for this study were the three-dimensional (sagittal, frontal, and transverse) by subject ensemble average peak lower extremity angles (ankle, knee, and hip), for each combination of roof angle and wearable device, calculated in visual 3D. The kinematics were analyzed with a two-way—4(intervention) X 3(slope)—repeated measure analysis of variance (ANOVA). Mauchly’s Test of Sphericity was used to determine the sphericity of the data. If Mauchly’s Test showed the data were spheric, then no correction was needed. If Mauchly’s Test indicated sphericity was violated, the Greenhouse-Geisser correction was used if epsilon was less than 0.75 and if epision was greater than 0.75 the Huyhn-Feldt correction was used to determine significance. Post hoc pairwise comparisons were used to determine specific differences between conditions. Data analysis was completed using SPSS v22 (IBM Corp. Armonk, NY) and *p*-values were set to 0.05.

Results

As hypothesized, the introduction of a sloped surface and the wearable interventions considerably altered lower extremity full flexion kneeling kinematics compared to level and no intervention deep kneeling. Of the nine outcome variables analyzed, four of these variables were significantly changed with the introduction of the sloped surface and seven of these variables were significantly changed with the introduction of a wearable device. The results highlighting the differences is in tables 1 & 2 and the comparison of kinematics can be found in Figures 5 through 9.

Sagittal

Ankle peak angles did not have a significant interaction between slope and intervention ($p=0.164$). Significant main effects for slope ($p\leq0.001$) and intervention ($p=0.009$) were present. Slope post-hoc pairwise comparisons revealed level ankle plantar flexion ($21.13^{0}\pm6.58^{0}$)— mean ± standard deviation)— was significantly different than ankle dorsiflexion at 15 degree ($2.23^{0}\pm3.10^{0}$) and 30 degree ($15.77^{0}\pm1.91^{0}$) slope. Also, ankle dorsiflexion at the 15 degree slope ($2.23^{0}\pm3.10^{0}$) was significantly larger than at the 30 degree slope ($15.77^{0}\pm1.91^{0}$). Intervention post-hoc pairwise comparisons uncovered that KS intervention dorsiflexion ($2.35^{0}\pm12.74^{0}$) was significantly different than BO intervention plantarflexion ($5.42^{0}\pm19.00^{0}$).

Knee peak angles did not have a significant interaction between slope and intervention ($p=0.150$). Significant main effects for intervention ($p\leq0.001$) were present. Intervention post-hoc pairwise comparisons revealed NO intervention knee flexion ($145.26^{0}\pm0.74^{0}$) was significantly larger than KS intervention knee flexion ($140.57^{0}\pm0.24^{0}$) and BO intervention ($140.58^{0}\pm0.89^{0}$). It was also shown that KP intervention knee flexion ($144.96^{0}\pm1.07^{0}$) was significantly larger than KS intervention ($140.57^{0}\pm0.24^{0}$) and BO ($140.58^{0}\pm0.89^{0}$) knee flexion.

Hip peak angles did not have a significant interaction between slope and intervention ($p=0.073$). Significant main effects for slope ($p\leq0.001$) and intervention ($p\leq0.001$) were observed. Slope post-hoc pairwise comparisons revealed that level hip flexion ($32.66^{0}\pm4.07^{0}$) was significantly smaller than hip flexion on both 15 degree ($49.70^{0}\pm4.94^{0}$) and 30 degree ($50.13^{0}\pm5.\ 87^{0}$) slopes. Intervention post-hoc pairwise comparisons indicated NO intervention hip flexion ($46.72^{0}\pm10.42^{0}$) was significantly smaller than KP intervention hip flexion ($50.25^{0}\pm8.21^{0}$) and significantly larger than KS intervention ($38.22^{0}\pm7.79^{0}$) and BO intervention ($41.45^{0}\pm6.39^{0}$) hip flexion. Additionally KP intervention hip flexion ($50.25^{0}\pm8.21^{0}$) was significantly larger than KS intervention ($38.22^{0}\pm7.79^{0}$) and BO intervention ($41.45^{0}\pm6.39^{0}$).

Frontal

Ankle peak angles did not have a significant interaction between slope and intervention ($p=0.377$). Significant main effects for slope ($p=0.001$) were present. Slope post-hoc pairwise comparisons revealed ankle inversion at zero degrees ($7.12^{0}\pm0.92^{0}$) was significantly different than ankle eversion ($2.14^{0}\pm1.36^{0}$) at thirty degrees. It is noteworthy to mention that ankle inversion at zero degrees ($7.12^{0}\pm0.92^{0}$) was trending to be significantly larger than ankle inversion ($1.50^{0}\pm1.83^{0}$) on a 15 degree slope ($p=0.052$).

Knee peak angles did not have a significant interaction between slope and intervention ($p=0.685$). Significant main effects for intervention ($p\leq0.001$) were present. Intervention post-hoc pairwise comparisons revealed the NO intervention condition abduction ($0.64^{0}\pm0.17^{0}$) was significantly different than BO intervention adduction ($2.13^{0}\pm0.31^{0}$). BO intervention adduction ($2.13^{0}\pm0.31^{0}$) was significantly larger than KP intervention knee adduction (0.13^0±0.24^0) and KS intervention knee adduction (0.12^0±0.56^0). Furthermore NO intervention condition abduction (0.64^0±0.17^0) was trending toward significantly different KP intervention knee adduction (0.13^0±0.24^0) with ($p=0.053$)

Hip peak angles did not have a significant interaction between slope and intervention ($p=0.485$). Main effects for slope ($p=0.499$) and intervention ($p=0.382$) were not significant.

Transverse

Ankle peak angles did not have a significant interaction between slope and intervention ($p=0.544$). Significant main effects for intervention ($p\leq0.001$) were present. Intervention post-hoc pairwise comparisons revealed NO intervention external rotation (8.72^0±1.36^0) was significantly smaller than KS intervention (15.18^0±1.83^0) and BO intervention (13.00^0±0.65^0) external rotation.

Knee peak angles did not have a significant interaction between slope and intervention ($p=0.406$). Significant main effects for intervention ($p\leq0.001$) were present. Intervention post-hoc pairwise comparisons revealed NO intervention internal rotation (6.52^0±0.68^0) was significantly different than KS intervention (0.41^0±1.95^0) and BO intervention (1.07^0±0.50^0) external rotation. Also, KP intervention internal rotation (5.00^0±1.74^0) was significantly different than KS intervention (0.41^0±1.95^0) and BO intervention (1.07^0±0.50^0) external rotation.

Hip peak angles did not have a significant interaction between slope and intervention ($p=0.105$). Significant main effects for slope ($p=0.014$) and intervention ($p\leq0.001$) were present. Slope post-hoc pairwise comparisons revealed zero degree hip internal rotation (9.31^0±2.69^0) was significantly smaller than hip internal rotation (14.57^0±1.90^0) at the 30 degree slope. Intervention post-hoc pairwise comparisons revealed NO intervention hip internal rotation (13.40^0±3.80^0) was significantly larger than KS intervention hip internal rotation (9.79^0±2.73^0). Additionally, KP intervention internal rotation (14.67^0±0.82^0) was significantly larger than KS intervention hip (9.79^0±2.73^0) and (11.07^0±1.49^0) BO intervention internal rotation.

Discussion

In this study, we determined and documented how the inclusion of different combinations of two interventions—knee pads (KP) and knee savers (KS)—can alter three-dimensional lower extremity kinematics during the resting posture in roofing when deep or near full flexion kneeling occurs while on different sloped surfaces. Overall, the addition of the interventions significantly altered all the lower extremity kinematics in the sagittal and transverse planes, and also the knee kinematics in the frontal plane. This was the first study to quantify the kinematic changes—due to wearable interventions—in the lower extremity during deep or near full kneeling while on a sloped surface, which is a common action taken by residential roofers.

Musculoskeletal disorders are caused by numerous factors and as such it is very difficult to determine what causes MSDs as they are reliant on the reaction of the individual worker—

physical and psychological—to the physical demands of the job. One common factor associated with MSD risk is extreme postures and to alleviate MSD risk induced by an extreme posture, an individual must be in an as neutral posture as possible. This was the basic question in this study; can the use of two third party wearable devices—one commonly used in construction (KP) and one designed to reduce MSD risk during a specific task (KS)—lessen the extreme posture encountered by residential roofers during a deep flexion or resting posture?

Two different factors—slope and intervention—were tested to characterize the influence of these interventions on the extreme posture in roofers during the relaxation/non-working phase. While the effect of slope is not easily controlled in an actual roof environment, it is important to consider how the intervention will alter the impact the slope has on lower extremity kinematics. Though there were no statistically significant interactions between slope and intervention, there were statistically significant main effects for both of the tested factors. The connection between these two interventions and lower extremity kinematics is an essential one in relation to MSD risk caused by extreme and awkward postures. What is important is regardless of how the slope influences lower extremity kinematics—as removing the sloped surface from a residential roofing environment is not possible—in what way does the intervention change the extreme posture. For example, while the knee pads could help with acute injuries or MSDs to the patellar tendon, they really didn’t change the extreme angles like knee flexion across the different slopes. However, the knee savers did induce a significant reduction the extreme posture in knee flexion across different slopes.

Several examples were observed wherein the inclusion of an intervention indeed reduced MSD risk caused by extreme posture by lessening the peak angle during that condition, which was different than what was observed in the previously KS studies (Gray et al., 2015; Stone et al., 2014a; Stone et al., 2017; Stone et al., 2014b). For example, knee flexion angle was about the same for all three sloped conditions, however the presence of a single intervention—KP or KS—caused a reduction in deep knee flexion during resting compared to no intervention. Hip flexion was increased as the slope increased however the addition of either the KS or BO interventions reduced hip flexion compared to NO intervention, which is a positive result from this study and in part confirms the hypothesis of this study. Ankle inversion and hip abduction were reduced with the KS and BO interventions compared to NO intervention. Knee rotations were far smaller with the KS and BO interventions compared to NO intervention. These are just a few representative observations with how the addition of the interventions reduced extreme postures. These changes do not necessary represent a statistically significant change between conditions, however it does signify an observable lessening in the awkward posture encountered by roofers when in deep or near full flexion during a resting posture while kneeling on a sloped roof surface. It is uncertain what causes MSD risk from extreme postures but larger than usual knee moments and forces are a product of extreme flexion angles during kneeling (Mikosz et al., 1988; Morrison, 1970; Nagura et al., 2002; Schipplein and Andriacchi, 1991; Seireg and Arvikar, 1975), the medial and lateral tibiofemoral and patellofemoral contact pressure increases as knee flexion gets larger (Hofer et al., 2011; Lee, 2014) and repetitive kneeling has been linked to knee osteoarthritis (Coggon et al., 2000; Cooper et al., 1994; Hofer et al., 2011). Not surprisingly, changes in knee biomechanics has been the most studied during deep kneeling tasks.

Nevertheless, severe ankle stress and imbalance was reported while kneeling on a 30 degree slope and increased hip osteoarthritis risk can be associated with kneeling (Jensen, 2008; Wang et al., 2017). Thus any strategy that has the ability to reduce large or extreme joint angles can be considered to reduce lower extremity MSD risk. The addition of the two interventions exhibited an ability to do this in several of the lower extremity kinematics and thus is a positive finding of this study.

That said, in one instance—ankle external rotation—the addition of the tested interventions in this study increased this angle compared to the NO intervention. Though the increase was not statistically significant, it is still important to consider any changes that might increase MSD risk, by increasing the extreme posture, when considering the usefulness of an intervention. One possible limitation in this study is the use of non- roofers. However the use of novice individuals is acceptable because it allowed for the observation of how extreme postures influence individuals when they first encounter a sloped working environment. Additionally, this study only investigated one ergonomic risk factor (awkward postures) and how the interventions will alleviated this risk. The effectiveness of these interventions, need to still be evaluated with respect to the other ergonomic risk factors.

Due to the fact that it is not well-defined what mechanisms prompt MSD injuries, and given that several different factors are strongly believed to stimulate MSD injuries, the testing of any wearable device must be comprehensive and consider all possible factors of increased MSD risk. Therefore future studies into the effectiveness of the knee pads and knee savers interventions to reduce MSD risk must include other ergonomic factors that are associated with roofing such as: repetitiveness, pace of work and duration. Furthermore, additional considerations for safety must be tested with the KS intervention to ensure the roofers are not placed at any increased falling risk, even though they might have a reduced MSD risk.

Conclusion

The addition of the knee pad and/or knee saver intervention was able to reduce many extreme postures in the lower extremity during deep/full kneeling in the resting posture of roof workers. However, one joint did encounter an adverse change in posture in posture with the addition of the intervention. This study has provided a sound basis for the use of third-party devices to reduce MSD risk due to lower extremity joint angles on a sloped surface, however further testing involving other MSD risk factors is needed prior to conclusive recommendations.

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Abbreviations

NO	No intervention KP Knee Pads

KS	Knee Savers
BO	Both interventions
MSD	Musculoskeletal disorder

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Highlights

- Extreme kneeling postures encountered by roofers may lead to musculoskeletal injury
- Wearable devices may reduce musculoskeletal injury risk on sloped surfaces
- Knee savers alter lower extremity kinematics in deep kneeling on sloped surfaces

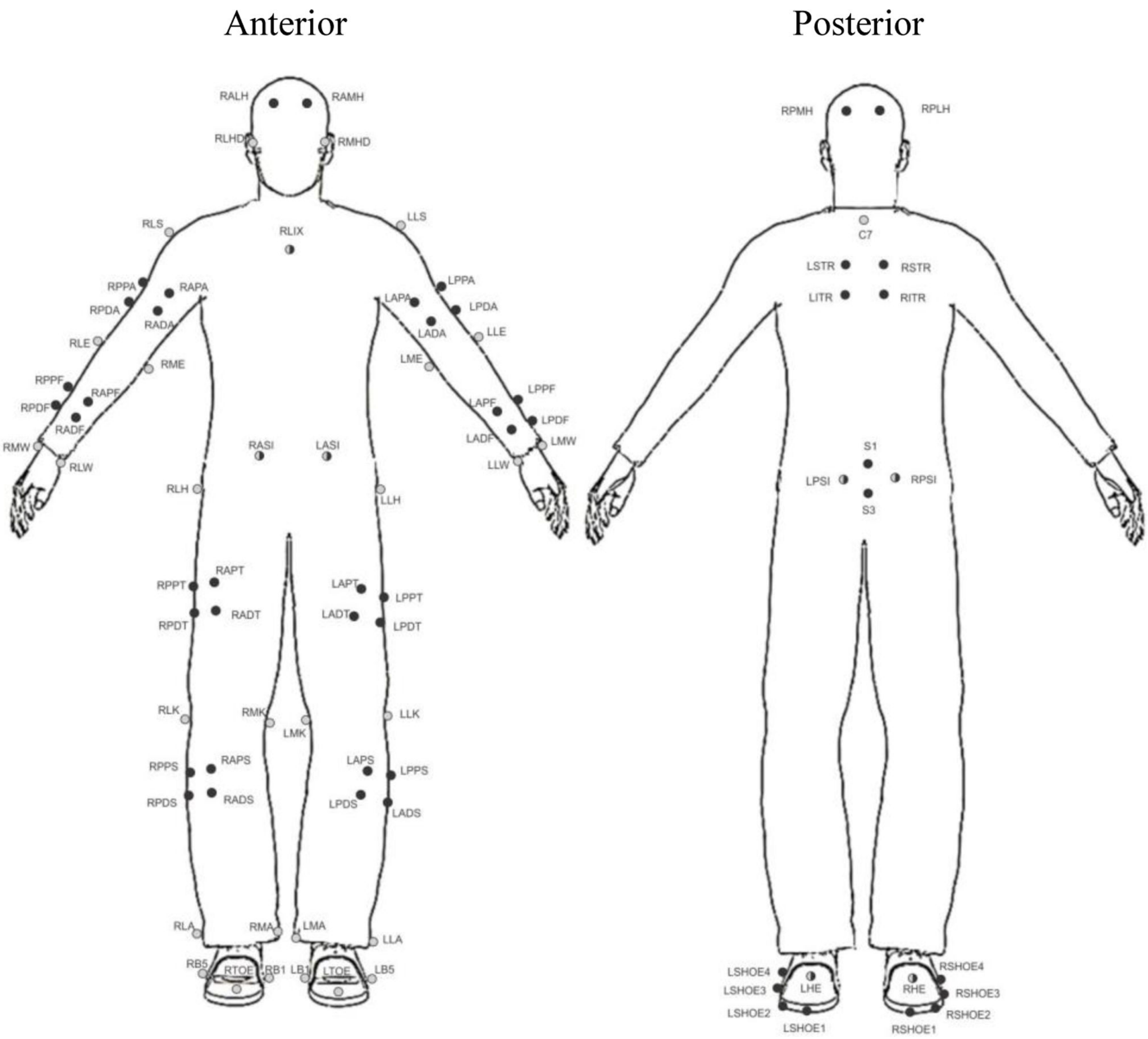

Figure 1.

Retro-reflective marker set utilized for recording human motion

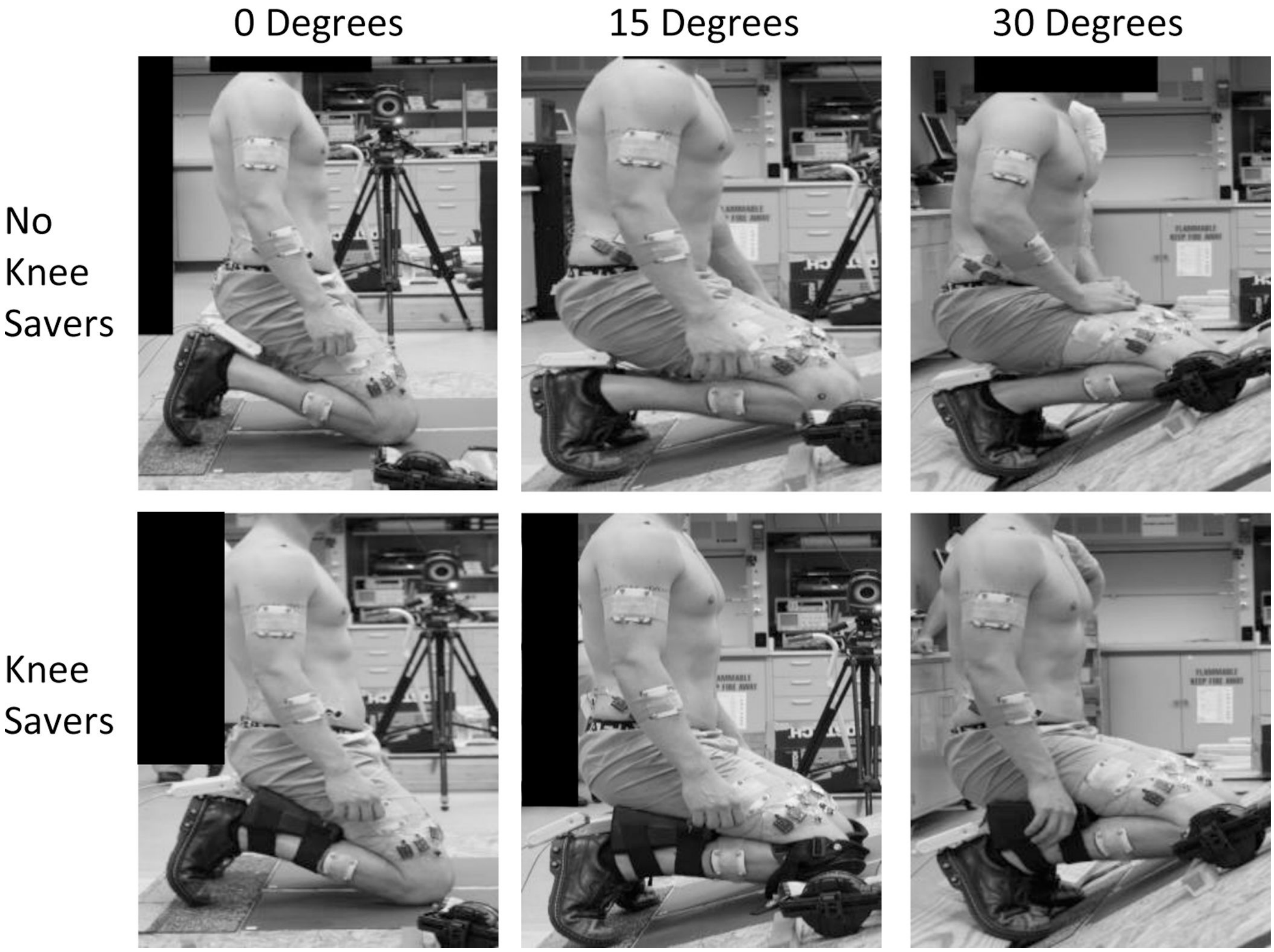

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Figure 2.

A subject in full/deep flexion resting posture on three different slopes: First column is 0 degrees, second column is 15 degrees, and third column is 30 degrees. The first row the subjects do not have knee savers and the second row, the subjects are wearing knee savers

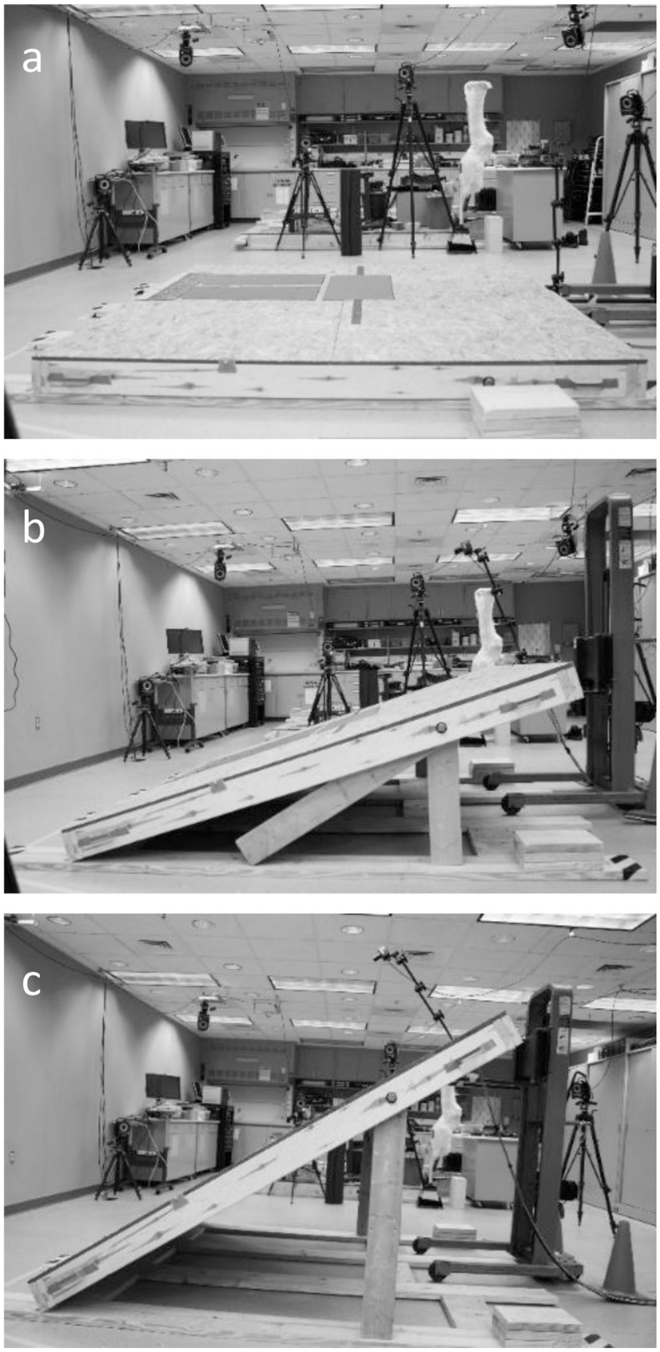

Figure 3.
Roof Simulator set at three different slopes: (a) 0 degrees, (b) 15 degrees, (c) 30 degrees

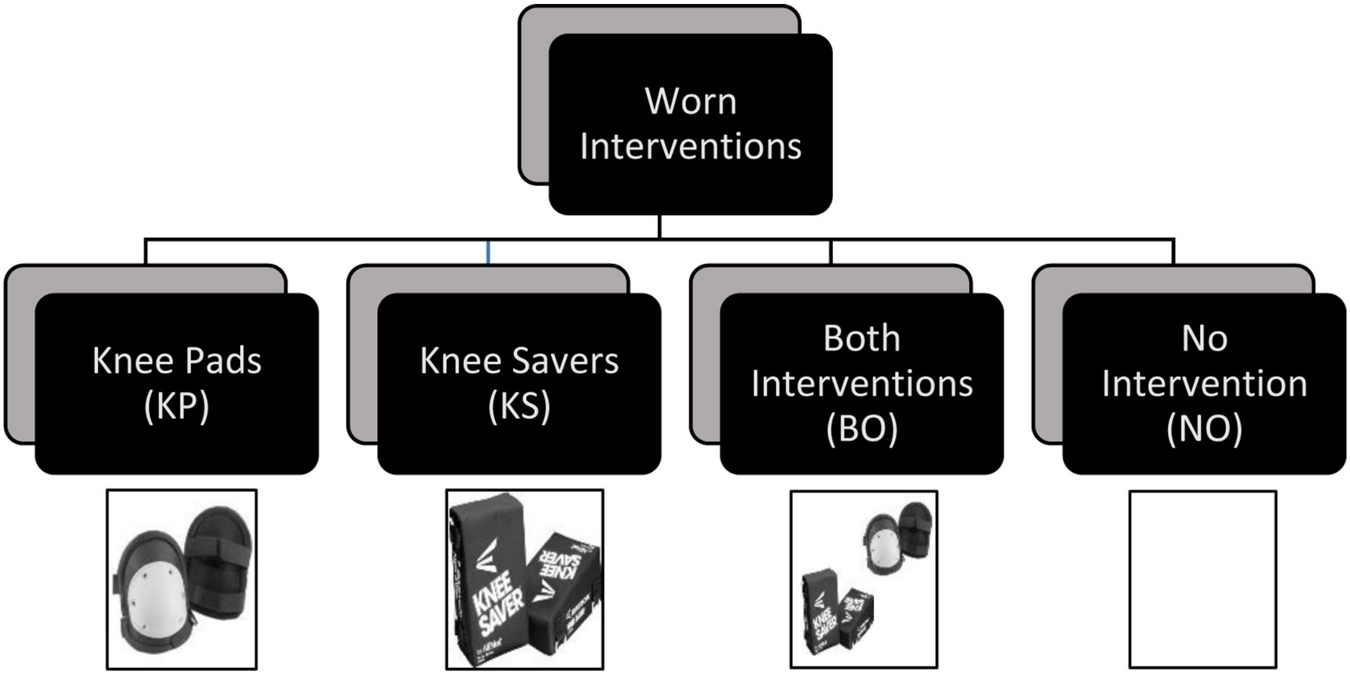

Figure 4.

Four scenarios tested for the effects of the wearable interventions

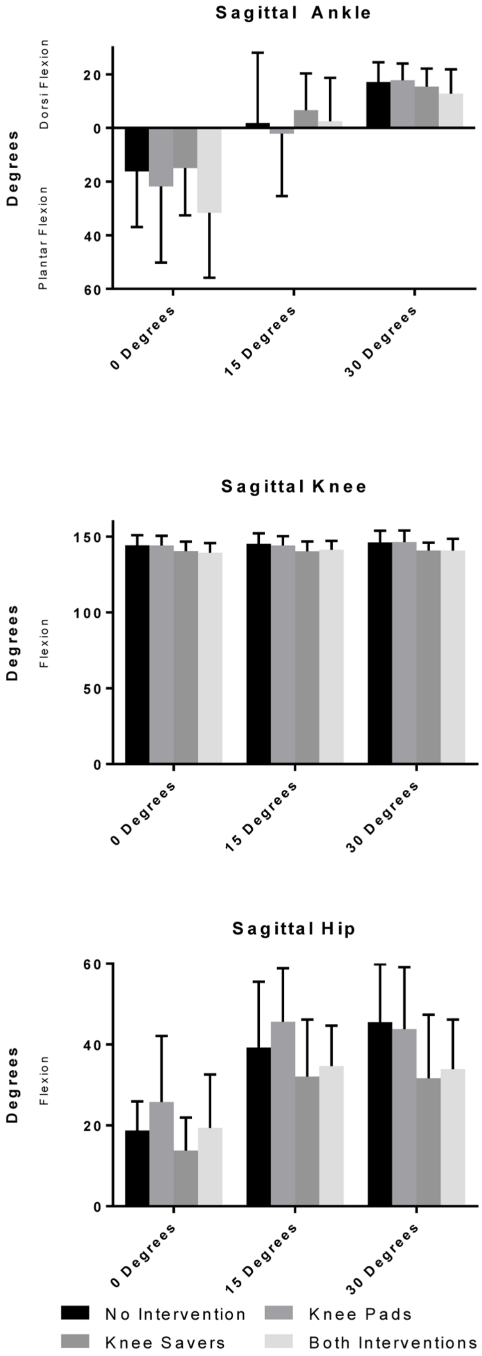

Figure 5.

Sagittal inter-subject lower extremity peak angles

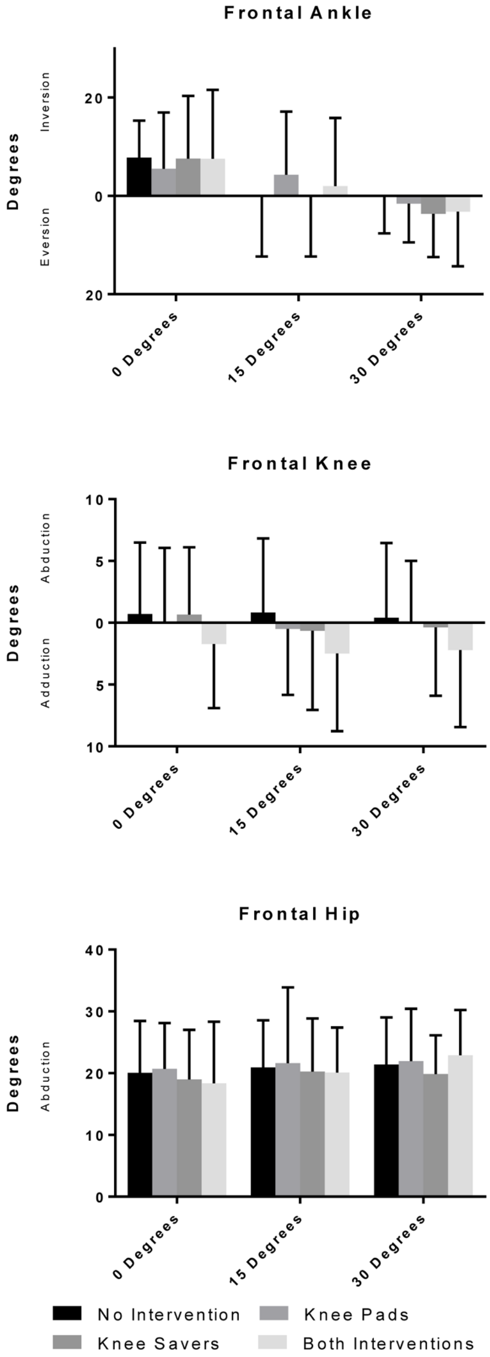

Figure 6.

Frontal inter-subject lower extremity peak angles

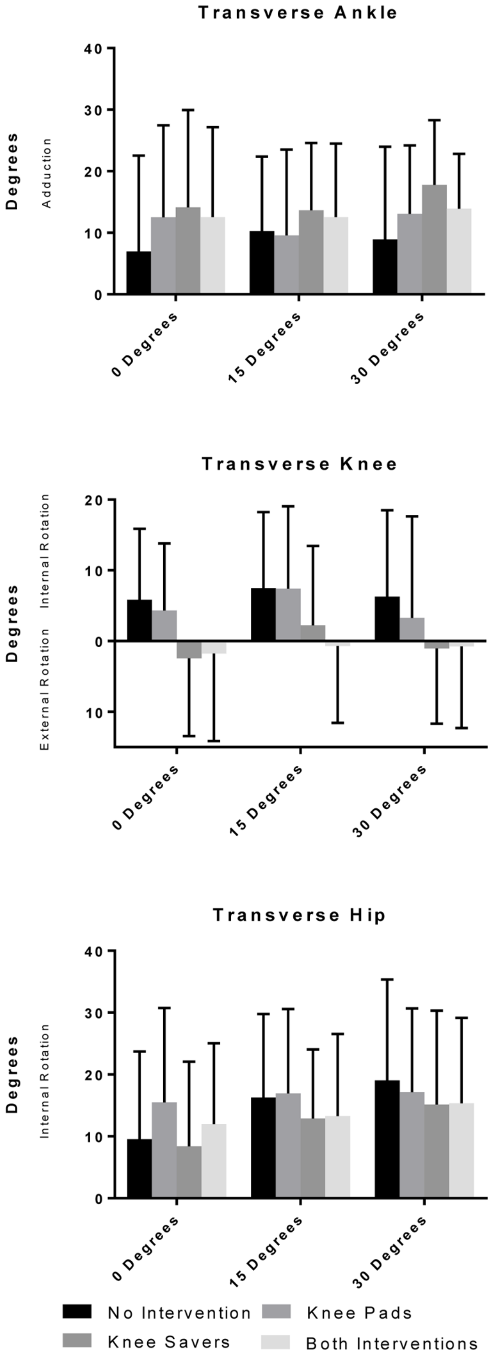

Figure 7.

Transverse inter-subject lower extremity peak angles

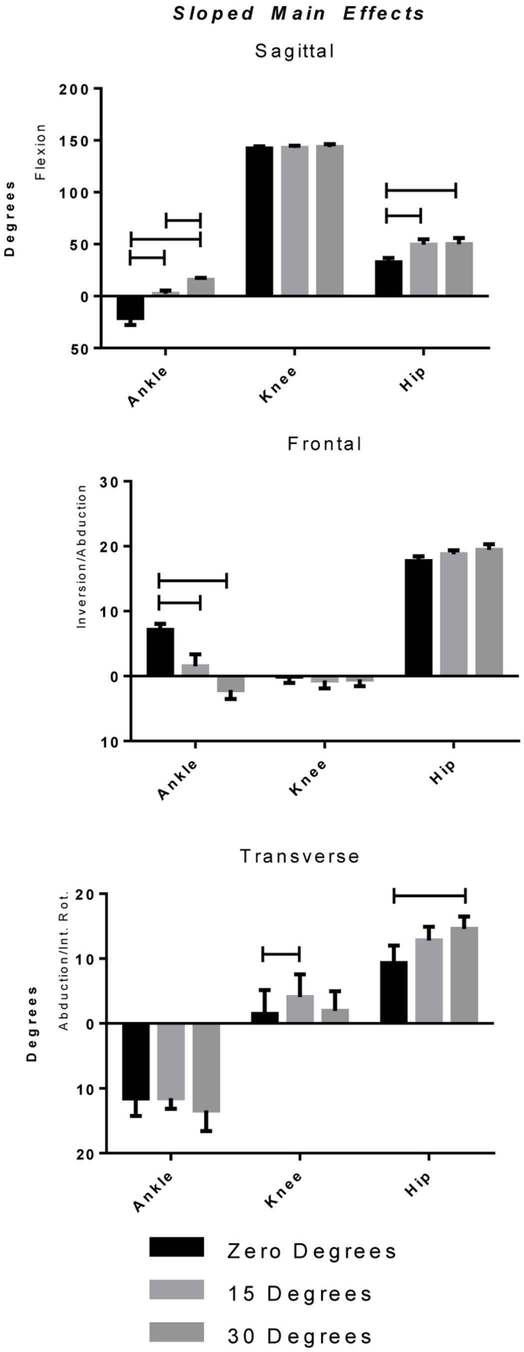

Figure 8.

Slope main effects

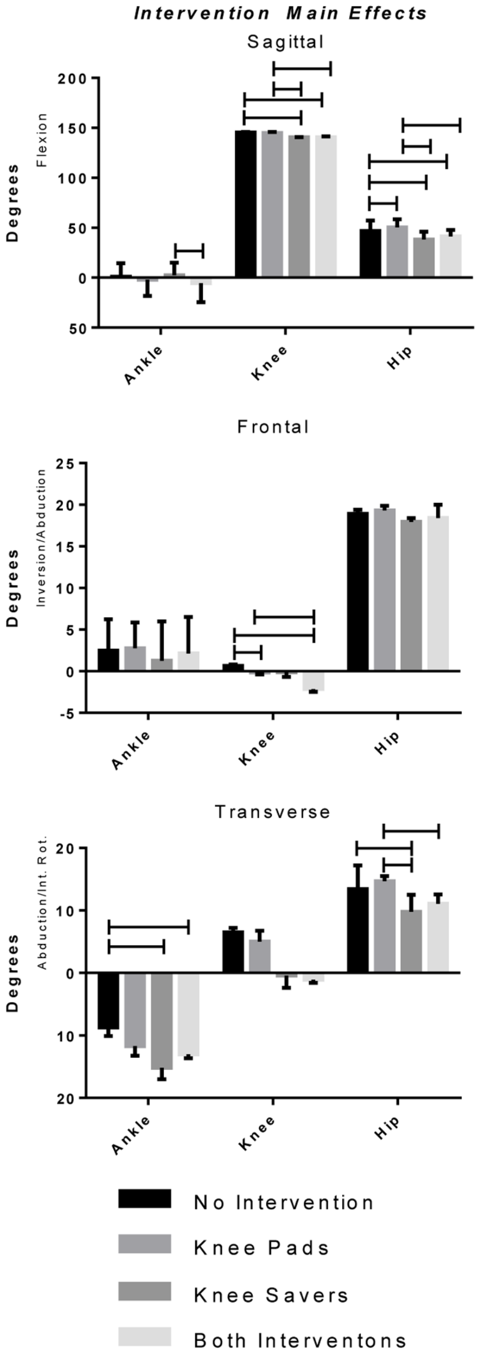

Figure 9.

Intervention main effects

Table 1.

Depicts statistical significant ($p \leq 0.05$) changes in the various testing conditions.

		Interaction	Main Effect Slope	Main Effect Intervention
	Ankle		†	†
Sagittal	Knee			†
	Hip		†	†
	Ankle		†	
Frontal	Knee			†
	Hip			
	Ankle			†
Transverse	Knee			†
	Hip		†	†

[†] indicates statistical significance.

Table 2.

Indicates how the intervention changed peak kinematics compared to no intervention.

		Knee Pads	Knee Savers	Both
Sagittal	Ankle			
	Knee	↓	↓	↓
	Hip	↑	↓	↓
Frontal	Ankle		↓	↓
	Knee			↑
	Hip	↑	↓	↓
Transvers	Ankle	↑	↑	↑
	Knee	↓	↓	↓
	Hip	↓	↓	↓