EFFECT OF WARM-UP ACTIVITY ON VERTICAL GROUND REACTION FORCES
IN BASKETBALL PLAYERS DURING DROP JUMP LANDINGS

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ABSTRACT

Effect of Warm-Up Activity on Vertical Ground Reaction Forces in Basketball Players

During Drop Jump Landings

Jacob Hinkel-Lipsker

Purpose: The purpose of this study was to examine the effect of certain warm-up activities on vertical ground reaction forces (GRF_v) during a drop jump landing.

Methods: Eight women and twelve men (mean age 22.6 ± 1.82 years) completed three warm-up activities on three separate days in a counterbalanced order: a passive stretching warm-up, a dynamic warm-up, and a no warm-up control. After completing each activity, participants were asked to perform eight drop jump landings on a force platform. GRF_v data was sampled at 1000 Hz during each landing, and the variables analyzed were: peak forefoot and rearfoot magnitude, forefoot and rearfoot rate of loading, and impulse.

Results: The dynamic warm-up had significantly greater values ($p < 0.05$) for forefoot peak magnitude, rearfoot peak magnitude, and forefoot rate of loading compared to the passive stretching and control conditions. Also, there were no significant differences among all activities for rearfoot rate of loading and impulse. **Conclusions:** The significantly greater values for forefoot peak magnitude, rearfoot peak magnitude, and forefoot rate of loading that the dynamic warm-up produced indicates that this activity may be effective in increasing muscular stiffness in the lower limbs. The failure of the passive stretching warm-up to reach significance indicates that this activity may not be effective in decreasing lower extremity muscular stiffness.

Keywords: ground reaction force, jumping, stiffness, stretching, stretch-shorten cycle

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CHAPTER 1

INTRODUCTION

Background of the Study

The amount of muscular stiffness in the lower extremities is a factor that should be taken into account for athletes who participate in jumping sports, such as basketball, volleyball, or gymnastics. For example, in a study conducted by Dufek and Bates (1991), they mentioned that the lower extremities are a primary injury site during jump landings. Also, they stated that more studies should be done to better understand the neuromechanical mechanisms associated with force attenuation during a jump landing. Furthermore, Watkins (1999) suggested there is an optimal level of muscular stiffness, since it seems that muscular stiffness can directly affect leg stiffness. According to him, the greater the level of muscular stiffness, the better those muscles are at absorbing strain energy, which leads to lower stress and strain on bones and joints. However, it is important to note that this study did not measure leg stiffness, so no connections between muscular stiffness and injury could be made.

In addition to its implications for injury, altering muscular stiffness in the lower limbs can also affect force production. For example, Wilson, Murphy, and Pryor (1994) stated that a stiffer musculotendinous unit could improve force production capabilities of the contractile component due to increasing the rate of shortening and improving initial force transmission. For a jumping athlete, this improvement in force production could contribute to a better jumping performance. On the other hand, a lower amount of muscular stiffness could be detrimental to jumping performance (Bradley et al., 2007).

Thus, lower extremity muscular stiffness is certainly a factor that affects the performance of jumping athletes.

While the scope of this study does not encompass recommending a means to prevent injury nor provide suggestions to improve jumping performance, collecting and interpreting vertical ground reaction force (GRF_v) data may be a way to examine changes in muscular stiffness (Denoth, 1986; James et al., 2010; Smith, 2009; Williams, 2004). In short, an increase in lower extremity muscular stiffness is correlated with an increase in peak GRF_v magnitude, rate of impact loading (time from impact with the ground to peak GRF_v), and a decrease in impulse (integration of the area under the curve of a GRF_v graph).

This examination of GRF_v can be used to test the effects of activities that compose warm-ups. If the goal of a pre-activity warm-up is to help limit injury and increase performance, interpreting GRF_v variables following a jump landing may provide insight as to how effective certain warm-up activities are on causing changes in muscular stiffness. For example, a commonly used pre-exercise activity is passive stretching. This type of warm-up can decrease muscular stiffness through decreasing muscular activation (Behm et al., 2001, 2004). However, passive stretching can be detrimental to jumping performance, as described by Kay and Blazeovich (2008). Conversely, a warm-up that incorporates the use of the stretch-shorten cycle (SSC) through ballistic activities has been shown to increase muscular stiffness (Bosco, 1982; Whitehead, 2001). This activity, which will henceforth be referred to as a dynamic warm-up, could help to limit bony injuries (Butler, Crowell, & Davis, 2003) and lead to an increase in jumping performance (Horita et al., 2002).

Statement of the Purpose

The purpose of this study was to examine the effects of warm-up activities on GRF_v during jump landings. A passive stretching warm-up, a dynamic warm-up, and a no warm-up control were the activities tested, and a drop jump was used to simulate a jump landing. Peak forefoot and rearfoot GRF_v magnitude, forefoot and rearfoot rate of loading, and impulse were the dependent measures used to examine the effects of warm-up activities on GRF_v .

Delimitations

1. The participants of this study were students at California Polytechnic State University, San Luis Obispo within the age range of 18-30.
2. Participants who were selected had, at minimum, recreational experience in playing basketball. This was required because landing properly from a jump can be considered a motor skill that improves with experience (Hoffman, Lieberman, & Gusis, 1997).
3. Testing was done in the Biomechanics/Motor Learning and Control laboratory on the first floor of the Kinesiology building at California Polytechnic State University, San Luis Obispo.
4. All participants were self-proclaimed to be in good health prior to testing and had no history of ankle, knee, or hip injury within the last year (Caulfield & Garrett, 2002).

Limitations

1. It is possible that the type of shoes worn in this study caused some variability in GRF_v results. While it was an inclusion criterion that the shoes worn for participation in this study were high-top, EVA mid-soled basketball shoes that had been worn for less than a year, the stiffness of these shoes were not quantified. Thus, the GRF_v results of this study may have been influenced by some variability in shoe sole stiffness.

Assumptions

1. Participants were honest with regards to their health history and current status.
2. Participants did not exercise or participate in any vigorous activity on the same day as testing occurred.
3. Participants wore shoes that they would normally wear during a jumping activity.

Research Hypotheses

Hypotheses

1. A passive stretching warm-up will result in a lower forefoot peak GRF_v magnitude during a jump landing relative to the control (no warm-up) activity, while the dynamic warm-up will show a higher peak forefoot GRF_v magnitude relative to the control.
2. A passive stretching warm-up will result in a lower rearfoot peak GRF_v magnitude relative to the control (no warm-up) activity, while a dynamic warm-up will show the highest peak rearfoot GRF_v magnitude relative to the control.

3. A passive stretching warm-up will result in a lower forefoot rate of loading relative to the control (no warm-up) activity, while a dynamic warm-up will have a higher forefoot rate of loading relative to the control.
4. A passive stretching warm-up will result in a lower rearfoot rate of loading relative to the control (no warm-up) activity, while a dynamic warm-up will have a higher rearfoot rate of loading relative to the control.
5. A passive stretching warm-up will show the highest GRF_v impulse relative to the control (no warm-up) activity, while a dynamic warm-up will have the lowest GRF_v impulse relative to the control.

Null Hypotheses

1. There will be no significant difference in peak forefoot GRF_v magnitude during a jump landing when comparing both the passive stretching and dynamic warm-up activities to the control (no warm-up) activity.
2. There will be no significant difference in peak rearfoot GRF_v magnitude during a jump landing when comparing both the passive stretching and dynamic warm-up activities to the control (no warm-up) activity.
3. There will be no significant difference in forefoot rate of loading during a jump landing when comparing both the passive stretching and dynamic warm-up activities to the control (no warm-up) activity.
4. There will be no significant difference in rearfoot rate of loading during a jump landing when comparing both the passive stretching and dynamic warm-up activities to the control (no warm-up) activity.

5. There will be no significant difference in impulse during a jump landing when comparing both the passive stretching and dynamic warm-up activities to the control (no warm-up) activity.

Significance of Question

A passive stretching warm-up has been shown to decrease muscular stiffness in the lower extremities, while a dynamic warm-up has shown the opposite effect. However, there is a lack of research comparing these two warm-up activities using force platform data. Thus, an analysis of GRF_v during jump landings after utilizing one of these warm-ups can provide a determination of whether or not an individual can prescribe these different warm-up activities individually in order to induce changes in GRF_v prior to a jumping activity.

Definition of Terms

Stiffness describes the ability of a component in the human body to resist deformation due to an external force. Compliance can be considered the reciprocal of stiffness, in that it explains the ability of a component to be deformed. (Latash & Zatsiorsky, 1993).

Muscular stiffness is a term describing the amount of attached actin-myosin cross bridges within a particular muscular fiber (Ford, Huxley, & Simmons, 1981; Hill, 1968; Howell, Chleboun, & Conaster, 1993; Julian & Sollins, 1975). The more attached cross-bridges, the higher the level of muscular stiffness. Conversely, a lower amount of attached cross-bridges can be defined as muscular compliance.

Passive stretching is a slow, static warm-up routine that invokes the use of an external force to provide resistance. Proper passive stretching involves lengthening a muscle group towards the end of its range of motion (Holt, Pelham, & Holt, 2008).

A dynamic warm-up is a series of activities that often include calisthenics such as squatting, lunging movements, and forward, lateral, and change of direction exercises (McMillian et al., 2006).

Ground Reaction Forces are forces that are provided by the support surface on which a movement occurs. They are derived from Newton's 3rd Law, which states that every action has an equal and opposite reaction, and represent the return of forces by the ground in reaction to the accelerations of body segments contacting it. They can be resolved into vertical, forward-backward, and side to side components (Enoka, 2008).

A force platform is a device that measures ground reaction forces in three directions. The resultant components (vertical, forward-backward, and side-to-side) represent the acceleration and mass of the body's center of mass when it comes into contact with the force platform (Enoka, 2008).

A drop jump is a task used to assess aspects of a jump such as takeoff and landing kinetics and kinematics. A participant is instructed to step off of a box, land on a surface, and then jump into the air again. This technique is beneficial to researchers because it allows them to choose the height of the box, and therefore they can control for jump height (Seegmiller & McCaw, 2003). The initial landing data of the drop jump is what was collected for this study.

CHAPTER 2

REVIEW OF LITERATURE

The purpose of this review is to investigate conclusions in previous works that have examined the role of muscular stiffness in the lower extremities, and how altering it can affect GRF_v during jump landings. One way to control muscular stiffness, according to McHugh and Cosgrave (2009), is to engage in a specific type of warm-up prior to physical activity. However, the extent to which a warm-up can affect muscular stiffness is not widely understood. This is largely due to the complexity of the leg segment, where components such as muscles, joints, tendons, and ligaments all contribute to observable segmental motion. Therefore, in sports that involve jumping, such as basketball and gymnastics, there is a need to better understand how to optimally alter muscular stiffness in the lower extremities since that body segment is where most force is generated during a jump and attenuated during a jump landing. In order to examine changes in muscular stiffness, vertical ground reaction force (GRF_v) data can be analyzed (Seegmiller & McCaw, 2003). First, this paper will review the ways in which muscular stiffness has been defined in previous research. This will be followed by a discussion surrounding central nervous system regulation of muscular stiffness. After this, the implications of altering muscular stiffness in the lower extremities on variables such as injury and jumping performance will be discussed. Finally, the effect of muscular stiffness on vertical ground reaction forces during jump landings will be reviewed.

Muscular stiffness has classically been defined as the amount of attached actin-myosin cross-bridges within a particular muscle fiber (Hill, 1968). These cross-bridges can be slightly bent or stretched, and together compose what is called the “short-range

elastic component” (SREC). An increased concentration of calcium (Ca^{2+}) ions within a muscle fiber can increase the amount of attached cross-bridges, which indicates a lesser ability for forces to deform the SREC. Other studies have similarly defined muscular stiffness. For example, Ford, Huxley, and Simmons (1981) sought to examine the relationship between the number of cross-bridge connections and stiffness in frog legs. To achieve this, they created tension in the tibialis anterior muscles using a stimulating current and measured stiffness using an analog circuit at different muscle lengths. They then analyzed the tension response to sudden muscle shortening and found that muscle compliance (or the reciprocal of muscle stiffness) increased proportionally to thin filament overlap of cross bridges. This indicates that the myosin heads are unexposed and therefore not connected. Studies conducted by Howell, Chleboun, & Conaster (1993) and Julian & Sollins (1975) have defined muscular stiffness in a similar manner.

Other researchers have used methods such as computerized models of the leg segment in order to visualize the effects of muscular stiffness. McMahon and Cheng (1990) developed one such model. They stated in the analysis of their model that the stiffness of the leg spring is a linear function of U , a horizontal Froude number related to forward speed and leg length and V , a vertical Froude number based on vertical landing velocity and leg length. While this study effectively described how stiffness affects the leg spring, they concluded their article by stating that the physiological variables that affect stiffness and the implications of the amount of stiffness in the lower extremities are still not well understood. This could be largely attributable to the fact that researchers in the field of biomechanics have yet to establish a common definition of stiffness that can be used as a working term in future studies. For example, Latash and Zatsiorsky (1993)

stated that the physical definition of stiffness differs from the term commonly used in the fields of biomechanics and motor control, where stiffness describes the ability of a component in the human body to be deformed and store and release elastic energy. They go on to detail how authors of a particular study need to take care to define which specific components of a body system they are testing, since there are many different ones that contribute to that system's overall stiffness. Furthermore, they recommended that the term "joint stiffness" be abandoned in future literature since that term can be misleading due to the amount of variables that can affect the overall stiffness of a joint.

Other authors seem to be in agreement with this assessment. Butler, Crowell, and Davis (2003) argued that the total stiffness about a specific joint can be altered by the individual stiffnesses of the contributing muscle, bone, tendons, ligaments, and cartilage. Similarly, Johns and Wright (1962) looked into how much each specific component contributes to overall joint stiffness. In their article, the authors examined a cat's wrist, which has many similar properties to a human metacarpophalangeal joint. They found that in the non-extremes of joint motion (where the tendons supply the bulk of support), the joint capsule itself supplies 47% of the torque required to move a joint in specific ranges, while muscle supplies 41%, tendons 10%, and skin 2%. This study showed that while there are multiple components that contribute to the overall stiffness of a joint, some components contribute more of the torque needed to move that joint than others do. It also provided evidence that muscle supplies a large amount of that torque.

Human cadaver studies, such as one conducted by Cook and McDonagh (1995), have also discussed the large role that muscular stiffness plays in the overall stiffness about a joint. To determine this, they measured muscle and tendon stiffness of the first

dorsal interosseus muscle using a stimulating current. Their results showed that at high levels of activation muscle and tendon stiffness were approximately equal. However, at low levels of activation muscular stiffness significantly decreased, while tendon stiffness remained the same. This means that while tendon stiffness does not change at different levels of stimulation, muscle stiffness does and therefore is more capable of changing due to extenuating circumstances. Thus, it is apparent that each component of the leg segment contributes to leg stiffness. Of these components, it can be argued that muscle makes one of the larger contributions to the overall stiffness of the leg segment. While this review is specifically focused on muscular stiffness, some of the following literature discussed investigates overall leg stiffness. However, it will be assumed that changes in leg stiffness are at least partially due to changes in muscular stiffness.

Central Nervous System Regulation of Muscular Stiffness

Muscular stiffness in the lower extremities can be altered via cognitive central nervous system (CNS) activation, as shown in a study by Devita and Skelly (1992). They reached this conclusion by investigating the effects of different types of jump landings in order to see if there was a difference in moments about lower extremity joints. The participants of this study were instructed to do a “soft” landing condition, where their knees were bent, and a “stiff” landing condition, where they landed with little knee flexion. Inverse dynamics were then used to estimate moments at the hip, knee, and ankle joints for each condition. The researchers found that the highest muscle moment and power values were highest at the hip joint in both activities. They stated that this is likely due to the fact that the hip joint muscles keep the entire upper body upright during

landing. In addition, the hip joint muscles assist the knee and ankle joint muscles in controlling segmental motion in the lower extremities. Furthermore, during stiff landings the relative contribution of the ankle joint muscles increased, which in turn decreased the relative contribution of the hip and knee joint muscles. This means that a person can consciously regulate control of jump landings.

The central nervous system (CNS) also can alter stiffness in a non-conscious fashion. For example, Enoka (1996) discussed how eccentric muscle contractions require a different command system from the CNS than purely concentric contractions do. This command system results in an altered recruitment of motor units and helps to attenuate the mechanical effects of impact forces. The outcome of this recruitment pattern helps to reduce the fatiguing of high-threshold motor units so they can be used when absolutely necessary, such as during emergency movements or athletic competition that utilize the stretch-shorten cycle (SSC). It also increases force output during the onset of a concentric contraction of the SSC, which implies that eccentric contractions result in a premotor muscle activation that is essential during jump landings. From a dynamical systems perspective, this feedback loop maximizes efficiency of muscle and helps to maintain attractor well stability (Wilson et al., 2008).

There are also extrinsic factors that can affect CNS regulation of muscular stiffness in the leg segment. One example of this is the type of surface that a person is landing on following a jump. Ferris and Farley (1999) investigated the interaction of surface stiffness and leg spring stiffness and found that individuals show an inverse relationship between the two (i.e. as surface stiffness increases, leg spring stiffness decreases and vice versa). While they noted this interaction, they acknowledge that the

mechanisms behind this action are not well understood, again due to the complexity of the leg spring. As of now, it is not clear whether this relationship is conscious (where the jumper adjusts their landing pattern according to the type surface that they are landing on) or non-conscious (where the amount of muscular stiffness is dictated by a feedback loop). They concluded that future studies should investigate the individual components' contribution to leg spring stiffness during landing activities. Based off of the findings of the authors discussed here, it is apparent that the CNS actively regulates muscular stiffness, and can cause changes in the level of stiffness almost instantaneously.

Implications of Changes in Lower Extremity Muscular Stiffness

The alterations in muscular stiffness that occur as a result of CNS regulation have widespread implications on multiple biomechanical factors during jump landings. For instance, one such factor is how the leg segment is able to attenuate shock and dissipate kinetic energy during landing. This ability is a direct result of the stiffness of the leg segment. According to Watkins (1999), the stiffness of the leg is dependent on the degree of stiffness in muscles that are controlling segmental motion about the lower extremity joints. Generally, a higher level of leg stiffness allows the leg to behave more like a spring, placing less of a load on bones and joints. Injury incidence and prevention in the lower extremities is beyond the scope of this review since leg stiffness was not quantified in this study, however numerous studies have looked at the relationship between leg stiffness and injury. As discussed previously, muscular stiffness influences leg stiffness to a considerable degree, and when viewed collectively, there seems to be an optimal level of leg stiffness for injury prevention. Too much leg stiffness means that an

individual is at a greater risk for soft tissue injury. On the other hand, too little leg stiffness may allow for excessive joint laxity (Butler, Crowell, & Davis, 2003). This means that a jumping athlete, may want to have a higher level of stiffness in order to prevent excess joint motion.

A lower amount of stiffness is caused by a decrease in neuromuscular activation (Richie 2001). As a result, there are studies that have investigated the relationship between decreased muscular activation and injury. A review by Richie (2001) described how a lack of neuromuscular control at the ankle joint can put a person at risk for injury as a result of excessive joint laxity. He calls this “functional instability,” and states that this is a combined result of decreased proprioception, muscle strength, muscle reaction time, and postural control. Scott and Winter (1990) also discuss the implications of ankle joint instability. They created a model in order to investigate the roles that muscles play during the landing phase of running and state that the plantarflexor muscles provide an anti-shear mechanism at the ankle joint and an anti-shear, anti-bending mechanism within the lower leg. They concluded that in order to properly engage these mechanisms, the correct amount of muscular activation is important. Again, this shows that an optimal level of muscular stiffness in the leg segment is necessary in order to best prevent injury.

Muscular fatigue also seems to be correlated with lower muscular activation. This is demonstrated in a study by Horita et al. (1996), who looked into the effects of SSC fatigue on joint stiffness, muscle reflex, and mechanical performance during drop jumps. Their subjects performed vertical jumps to the point of exhaustion, and then performed drop jumps. Muscle activation was measured using surface EMG attached to the vastus lateralis muscle. Joint moments were also estimated using inverse dynamics calculations.

In short, they found that stiffness of the vastus lateralis decreased with fatigue, as a result of decreased muscular activation. They hypothesized that this is due to a decrease in the number of attached cross-bridges, which is in line with how other studies previously discussed in this review define muscular stiffness (Hill, 1962; Ford, Huxley, & Simmons, 1981; Howell, Chleboun, & Conatser, 1993; Julian & Sollins, 1975). Therefore, fatigue can decrease muscular stiffness through a decrease in motor unit recruitment. Again, these studies correlate stiffness with injury. However, the purpose of this review is to provide an overview of the literature surrounding muscular stiffness in the lower extremities, not to offer recommendations for injury prevention.

Muscular stiffness in the leg segment can also affect an individual's jumping performance (Bradley et al., 2007). This is due to the fact that the leg behaves like a spring, and its damping qualities can help or hinder the ability of a person to jump in the air after landing. In investigating this phenomenon, Bradley et al. (2007) compared the effects of three different warm-up activities on drop jump performance. Two of the activities, static stretching and proprioceptive neuromuscular facilitation (PNF) of the lower extremities, can decrease muscular stiffness. On the other hand, ballistic stretching engages the SSC, and can therefore increase or have no effect on muscular stiffness. This study also included a no-stretching control condition (the effects of warm up activities on muscular stiffness will be discussed in greater detail later in this review).

In the study above, researchers found that immediately following the warm-up condition subjects showed a decrease in jumping performance in the static and PNF activities, and no change in the ballistic stretching task compared to the control condition. The researchers also collected jumping height data 15 minutes after each warm up

condition. They discovered that there was no difference in vertical jump height for any condition. According to Bradley et al. (2007), this is due to a recovery of voluntary muscle activation and increased musculotendinous stiffness since an acute bout of stretching does not cause permanent changes in the contractile properties of the leg muscles.

The conclusions that Bradley et al. (2007) reached have also been supported by Horita et al. (2002). The goal of their study was to look into how stiffness in the knee joint muscles can affect vertical takeoff speed following a drop jump. To accomplish this, they collected EMG data at the subjects' vastus lateralis muscles in order to record muscle activation levels before and after landing from the drop jump. Kinematic and kinetic data were also recorded in order to estimate knee joint moments. In collecting this data, they were able to calculate stiffness through a linear regression of the moment/angle relationship of the knee joint. They found that drop jump performance (takeoff velocity) correlated positively with stiffness at the initial impact phase of the drop jump landing and the period from the initial impact phase to the onset of push-off. In discussing these results, the researchers stated that the correlation between muscular stiffness and jumping performance is likely due to the fact that initial high stiffness can be transferred to the concentric phase of jumping through high series elastic component stiffness. The authors of this study also theorized that muscle strength, rate of force development, and fiber composition can influence muscular stiffness, and differences among these factors may have caused variation between subjects.

How Warm-Up Activities Can Affect Muscular Stiffness

As noted in the previous section, alterations in muscular stiffness in the lower extremities have implications for both injury and performance. Under this assumption, many researchers have looked into ways to make these alterations optimal prior to any sort of jumping activity. One type of warm up activity, passive stretching, has been thoroughly investigated in the past as a way to optimally modify muscular stiffness. Behm et al. (2004) compared the effects of an acute bout of passive stretching compared to a no stretching control condition. They examined maximum voluntary contraction (MVC), balance, muscle reaction time, and movement time as dependent measures in both activities. While there were no differences in MVC between the two activities, the control condition showed better balance and a decrease in muscle reaction time and movement time. An earlier study by Behm et al. (2001) investigated the effects of prolonged static stretching on muscular force loss. This study did show that stretching results in a decrease in MVC. Also, the peak EMG data collected in this study indicated a decrease in muscular activation after a stretching condition. Their findings suggest that passive stretching can significantly decrease neuromuscular activation, and therefore muscular stiffness, prior to a jumping activity.

Furthermore, Kay and Blazeovich (2008) investigated the effects of passive stretching on the mechanical properties of muscles and tendons. The researchers estimated joint moments using kinematic and kinetic data during plantar flexion trials for a rested (non-stretching) and stretching condition. They also collected normalized RMS EMG from the triceps surae muscles and used ultrasound imaging of the Achilles-gastrocnemius muscle-tendon junction to observe changes in tendon displacement. They

discovered a decrease in peak EMG amplitude after stretching that recovered after 30 min. This shows that stretching caused a short-term decrease in muscular activation. Also, while Achilles tendon length increased following a stretching trial, the researchers detected no change in tendon stiffness. However, post-stretch trials showed a decrease in muscular stiffness. This study highlighted the idea that overall leg stiffness is more influenced by muscular stiffness compared to tendon stiffness. Overall, it seems that a passive stretching warm up can reduce muscular stiffness in the legs prior to jumping activities, which may be detrimental to an athlete when considering the performance implications discussed earlier in this review.

While passive stretching has been shown to decrease muscular stiffness, studies such as one conducted by Bosco et al. (1982) have found that dynamic exercise involving the use of the SSC increased muscular stiffness. This experiment compared kinetic and EMG data of squat, countermovement, and drop jumps. The countermovement jumps (which utilize the SSC) show the highest level of motor unit activation. This implies that muscular stiffness increases after movements that invoke the SSC since higher motor unit activation leads to a greater number of attached actin-myosin cross-bridges.

In addition, a study by Whitehead et al. (2001) investigated the effects of repeated eccentric contractions (such as SSC movements) on membrane damage at the sarcomere level. They found that repeated contractions were responsible for this, and as a result change calcium (Ca^{2+}) ion homeostasis, an increase in calcium movement, and development of contracture. This process causes an increase in passive tension of muscle and an increase in stiffness. This concept had also been postulated in previous works. Hill (1962) described how sarcomere tears can allow a greater influx of calcium ions, and

therefore can alter the stiffness of the short-range elastic component via a greater number of attached actin-myosin cross-bridges. Taken together, these studies strongly suggest that dynamic exercise can cause an increase in muscular stiffness through changes at the muscle fiber level. In short, if an individual is interested in increasing muscular stiffness prior to a jumping activity, then he or she should engage in a specific dynamic warm up.

Measuring Ground Reaction Forces to Determine Muscular Stiffness

One method that researchers use to measure the relative amount of muscular stiffness in the leg segment is through the interpretation of vertical ground reaction forces (GRF_v). These are external forces that act in opposition to the body making contact with the ground as a result of gravity. The way these forces interact with the landing body segment are determined by intrinsic factors. For instance, changes in GRF_v reflect alterations in segmental control and system stiffness. As a result, decreased muscular activation is reflected by an increased GRF magnitude (Denoth, 1986). Also, James et al. (2010) investigated the effect of neuromuscular fatigue on jump landing dynamics. They used both maximum isometric squats and submaximal cycling as their fatiguing exercises. RMS EMG and force platform (GRF_v) data were collected during drop jump landings for both the fatigued and rested conditions. The GRF_v variables obtained were first and second force peaks, average loading time to those peaks, and impulse (integrated area under a force/time curve). They found that compared to a rested condition, the fatigued condition showed significant decreases in second GRF_v peak and impulse. While first peak and loading rate differences were not significant, they still showed large effect sizes. They also showed that in a fatigued condition, EMG amplitude decreased in the 61-

90 ms time frame post-contact in the vastus medialis, biceps femoris, and gastrocnemius muscles. These results indicated that a decrease in muscular activation can be detected by GRF_v peak magnitude, loading rate, and impulse variables.

Similarly, Smith et al. (2009) sought to find a fatigue difference on frontal plane knee motion, EMG amplitude, and GRF_v magnitude. They also investigated whether an individual's gender could affect these variables. While they did not find a gender difference, they did find that fatigue induced a lower peak GRF_v magnitude upon landing from a drop jump. They concluded that this could be indicative of a change in lower extremity stiffness. This again highlights the idea that changes in muscular stiffness are shown through changes in GRF_v variables.

A study conducted by Williams et al. (2004) showed an interaction between stiffness and increased loading rates that also supports the conclusions of Smith et al (2009), James (2010) and Denoth (1986). They investigated differences in running patterns between high-arched and low-arched runners. According to the authors, high-arched runners have a stiffer gait pattern than low-arched runners do, most likely due to the fact that high-arched runners exhibit earlier activation of the knee extensor muscles. In conjunction with this, the high-arched runners in their study exhibited increased loading rates compared to their low-arched counterparts. They recommend that further study needs to be conducted to investigate loading rates during running. Thus, it is apparent that collecting force platform data is an effective way to detect changes in muscular stiffness.

Taken together, the studies that have been reviewed here show the various ways in which stiffness has been defined and the settings in which stiffness has been examined.

Although there is a large amount of research that has investigated this topic, the complexity of muscular stiffness has yielded equivocal results. As noted previously, the amount of muscular stiffness in the legs can be interpreted through the analysis of GRF_v during jump landings (Denoth, 1986; Williams et al., 2004; Smith et al., 2009; James, 2010). Thus, the purpose of this study will be to investigate if certain warm-up activities alter GRF_v during a jump landing. This will be done by comparing a passive stretching warm-up and a dynamic warm-up's individual effects on GRF_v to a no warm-up control condition during drop jump landings. Ultimately, the results of this study will help to clarify whether these two warm-up techniques (when done exclusively) yield a difference in landing forces for jumping athletes.

CHAPTER 3

METHODS AND PROCEDURES

The purpose of this study was to examine the effects of warm-up activities on GRF_v during jump landings. The GRF_v components that were investigated after landing were peak magnitude, rate of loading, and impulse. The warm-up activities that were used to alter muscular stiffness were a passive stretching warm-up and a dynamic warm-up. These were compared to a no warm-up control condition. It was hypothesized that the dynamic warm-up would result in a higher rate of loading and peak magnitude, and lower impulse relative to the control. Also, this study hypothesized that the passive stretching warm-up would show a lower rate of loading and peak magnitude, and higher impulse relative to the control.

Participants

20 participants (8 women and 12 men, 22.6 years old $\pm$ 1.82) were recruited on a volunteer basis from a population of students in the age range of 18-30 at California Polytechnic State University, San Luis Obispo. Previous research has shown that women have different landing strategies than men do (Fagenbaum & Darling, 2003). To account for this, both men and women were recruited and gender was used as a predictor variable during data analysis. All participants were recruited from within the Cal Poly, San Luis Obispo Kinesiology Department and ASI Recreation Center.

Inclusion criteria for participants included recreational experience playing basketball. Experience was needed because, according to McKinley and Pedotti (1992), landing from a jump is a motor skill where those with experience show different joint

movements compared to novices. Malinzak et al. (2001) have defined recreational participation as participation in a given sport one to three times a week without following a professional training regimen. Participants were self-proclaimed to be in good health. Basketball was chosen due to the frequency of jumping during competition. Also, in order to be included participants were required to own and wear high-top basketball shoes with EVA midsoles that were purchased less than one year prior to testing. These shoes were required to help limit any confounding effects of shoe type. Exclusion criteria were injury to the spine or lower limbs within the last year, slight lower extremity injuries such as ankle sprains within six weeks of testing, neurological disorders that affect the lower extremities, diabetes, and a BMI of ≥ 30 .

All participants were cleared for participation using the Physical Activity Readiness Questionnaire (PAR-Q, Canadian Society for Exercise Physiology, 1994) and gave informed consent prior to participation in this study. The Human Subjects Review Committee at California Polytechnic State University, San Luis Obispo approved the methods and procedures for this study. All testing occurred in the Biomechanics/Motor Behavior laboratory in the Kinesiology Department at California Polytechnic State University, San Luis Obispo.

Procedures

The participants in this study were tested on three separate occasions. For each occasion, the participant completed a different warm-up activity prior to having their jump landing GRF_v measured. The order of these warm-up activities was counterbalanced. The warm-up activities were a passive stretching warm-up, a dynamic

warm-up, and a no warm-up control. In order to eliminate confounding effects of daily routine that may vary across participants, individuals were asked show up for testing in the morning. After giving informed consent, participants completed a familiarization trial where they performed drop jump landings ten times.

Passive Stretching Warm-Up Protocol

This protocol, which is described in detail by Holt, Pelham, and Holt (2008), involved two specific stretches. One involved stretching the hip extensors (biceps femoris, semimembranosus, semitendinosus, and gluteus maximus). For the initial phase of this stretch, the individual being stretched lied on his or her back with one leg flat on the table and the other raised as high as possible with the knee in an extended position (see Figure 1). The researcher was one on knee, with the opposite foot on the table and his shoulder pressed against the participant's leg in the air. For the stretching phase, the participant was instructed to pull the leg towards his or her head while the researcher applied light pressure in that direction. Also, the participant was told to mention any discomfort that was occurring. This stretch was carried out for 30 seconds. The hip extensors on the other leg were then stretched. This process was repeated for a total of two minutes of stretching.

The final stretch was done on the plantar flexor muscles (gastrocnemius, soleus, plantaris, tibialis posterior, fibularis longus, fibularis brevis). The participant was instructed to go into a seated position, with the knees fully extended, the legs straight, and the back in ideal posture. He or she was then asked to hold the ends of a towel and pull it around the foot, so that the ankle was dorsiflexed as much as possible. Then, the

participant was asked to pull on the towel to dorsiflex the ankle into its new, lengthened position. This protocol was also carried out for 30 seconds, completed on the opposite leg, and then repeated for a total time of 2 minutes. (see Figure 2).

Figure 1

Hip Extensor Stretch

Figure 2

Plantar Flexor Stretch

Dynamic Warm-Up Protocol

This warm-up activity incorporated ballistic, sagittal plane movements that utilized the stretch-shorten cycle. A study conducted by McMillian et al. (2006) utilized similar activities. The drills were performed at a slow-to-moderate pace across a 20-meter segment, followed by 10-15 seconds of rest and then a return to the starting point. These exercises were verticals, skips, and shuttle sprints (see table 1). The activities were repeated twice, for a total of 3 repetitions. This entire process lasted for approximately 10 minutes. Prior to engaging in this warm-up, participants were given a verbal and visual description of each exercise.

Table 1

Movement Drills—3 repetitions of each were completed, with 10-15 seconds of rest between each exercise

Exercise	Execution
Verticals	Run forward on the balls of the feet, raising the knees to waist level and maintaining a tall, upright stance. Use strong arm action to support the movement. Hands should move from waist to chin level with an approximately 90° bend in the elbows throughout. There should be no backswing of the legs with this drill.
Skips	Step and then hop, landing on the same leg, followed by the same action with the opposite leg. Use strong arm action to support the movement. Hands should move from waist to chin level with an approximately 90° bend in the elbows throughout. When the right leg is forward, the left arm swings forward and the right arm is to the rear. When the left leg is forward, the right arm swings forward and the left arm is to the rear.
Shuttle Sprints	Run at a moderate pace to the 20-yd line. When nearing the line, slow the movement, make a quarter-turn clockwise, plant the left foot parallel to the line, and squat or bend in order to touch the ground at the line. Run back to the starting line, turning counterclockwise to touch the ground with the right hand. Run back to and through the 25-yd line, gradually accelerating to near maximum speed.

No Warm-Up Control Protocol

For this activity, participants were asked to perform eight drop jump landings immediately upon arrival. There was no specified duration of rest between their arrival for testing and the jump landings. The purpose of this activity was to collect an individual's GRF_v data in a rested condition, and thus participants did not complete a warm-up activity during the testing session or prior to arrival. Also, since participants were asked to arrive for testing in the morning, an assumption for this activity was that they engaged in a minimal amount of daily living activities prior to the testing session. Therefore, the data from this activity could be used as a control to compare to GRF_v data collected from the passive stretching warm-up and dynamic warm-up activities.

Data Collection

After completing the protocol for each given warm-up activity, participants performed eight drop jump landings. When performing a drop jump landing, participants were asked to step off of a 37 cm box (about the height of two stairs) with their dominant foot and land bilaterally with their dominant foot on the force platform (see Figure 3). A drop landing was chosen as the task in order to prevent any countermovement occurring prior to a jump, which could have caused an increase in muscular stiffness in the lower extremities (Fukashiro, Hay, & Nagano, 2006). In addition, the participants were not given any instruction as to how to land, but were encouraged to land as they normally would during an athletic competition, while ensuring that both feet were hitting the floor simultaneously.

During each landing, GRF_v data was collected using a Kistler force platform 2812A (Kistler Instrument Corp., Switzerland) set into and flush with the floor of the laboratory. This data was collected at a sample rate of 1000 Hz, and was recorded from 10 ms prior to contact with the ground until 200 ms after contact. This time frame for collecting GRF_v data is a duration that reliably captures relevant GRF_v data (James, 2007). This data was processed using Bioware v 5.1.3.0 (Kistler Instrument Corp., Switzerland) and reduced into five discrete variables. Two of these variables were peak force magnitudes, which were measured as the highest vertical ground reaction force during the forefoot and rearfoot portions of the landing. Rate of loading was measured as the average slope to the forefoot peak and rearfoot peak. Impulse was measured as the mathematical integration of the area under the force/time curve from initial contact with the ground to 200 ms after contact with the ground (see Figure 4).

Figure 3

Drop Jump Landing onto Force Platform

Figure 4
Sample GRF_v Graph

Data Analysis

To investigate the effects of each warm-up condition on GRF_v, the means for each participants' eight trials for all five GRF components: (1) peak forefoot magnitude (F1), (2) peak rearfoot magnitude (F2), (3) rate of loading to forefoot peak (F1LR), (4) rate of loading to rearfoot peak (F2LR), and (5) impulse were calculated. All comparisons were within-subject and not normalized.

All data was analyzed using JMP Version 10.0 (SAS Institute, Inc., Cary, N.C.), and the level of significance was set at 0.05. Assumptions of normality and equality of variance were checked. However, it was found that a log transformation of the rate of loading forefoot peak was needed to address the equality of variance assumption. All data was normally distributed. Next, a multivariate analysis of variance (MANOVA) was then

used to compare the effects of warm-up activities on all dependent variables, with blocking for the subject variable to test within-subject. Significant main effects were further analyzed using a Tukey HSD post hoc test.

CHAPTER 4

RESULTS AND DISCUSSION

The purpose of this study was to examine the effects of warm-up activities on vertical ground reaction forces (GRF_v) during jump landings. The independent variables tested were the warm-up activities, while the dependent measures were five GRF_v components: peak forefoot magnitude, peak rearfoot magnitude, forefoot rate of loading, rearfoot rate of loading, and impulse. This chapter will discuss the results, statistical analysis, and findings of this study. It will first summarize the means of each GRF_v variable that was examined. Next, it will examine the whole model MANOVA that was used to compare the effects of warm-up activities to GRF_v variables. After this, it will describe the Tukey post-hoc tests that were utilized in order to find the effects of each activity on GRF_v. Finally, it will discuss these results in relation to the hypotheses postulated in Chapter 1 of this thesis.

GRF_v Results

The GRF_v variables' means and standard deviations for each warm-up activity are shown in Table 2 and Figures 5-9. The dynamic warm-up produced a significantly higher mean peak forefoot magnitude (F1, 2204.24 N), mean peak rearfoot magnitude (F2, 894.95 N), and forefoot rate of loading (F1LR, 39704.98 N/s). Rearfoot rate of loading was also the highest of the three warm-up activities, but did not exhibit statistical significance (F2LR, 4496.91 N). This activity also produced a lower impulse (169.92 Ns) compared to the passive stretching condition (173.69 Ns), but was about equal to the control condition (169.54 N). The passive stretching condition produced the lowest mean

values for peak forefoot magnitude (1906.23 N), peak rearfoot magnitude (823.31 N), and forefoot rate of loading (32875.84 N/s). The mean value for rearfoot rate of loading (3232.32 N/s) was higher than the value for the control condition (3953.35 N/s).

Table 2

Effect of warm-up activities on GRF_v means and standard deviations during a jump landing. The dynamic warm-up for the F1, F2, and F1LR variables exhibited significantly higher values than the control and passive stretching activities, while there was no significant differences in variables between the passive stretching and control activities.

(*= $P < 0.05$)

Variable	Passive Stretch	Dynamic	Control
F1 (N)	1906.23 $\pm$ 522.02	2204.24 $\pm$ 568.34 *	2010.15 $\pm$ 595.71
F2 (N)	823.31 $\pm$ 212.24	894.95 $\pm$ 223.84 *	836.95 $\pm$ 187.72
F1LR (N/s)	32875.84 $\pm$ 9621.52	39704.97 $\pm$ 11682.37 *	35021.93 $\pm$ 11353.81
F2LR (N/s)	4384.51 $\pm$ 3232.22	4496.91 $\pm$ 3059.43	3953.45 $\pm$ 2918.57
Impulse (Ns)	173.69 $\pm$ 19.17	169.92 $\pm$ 19.67	169.54 $\pm$ 20.06

Figure 5

Effect of warm-up activities on mean peak forefoot GRF_v during a jump landing. The dynamic warm-up had a significantly greater landing force than the control ($*=P<0.05$).

Figure 6

Effect of warm-up activities on mean peak rearfoot GRF_v during a jump landing. The dynamic warm-up had a significantly greater rate of loading than the control ($*=P<0.05$).

Figure 7

Effect of warm-up activities on mean forefoot rate of loading during a jump landing. The dynamic warm-up had a significantly greater rate of loading than the control ($*=P<0.05$).

Figure 8

Effect of warm-up activities on mean rearfoot rate of loading during a jump landing.

There were no significant differences among warm-up activities.

Figure 9

Effect of warm-up activities on mean impulse during a jump landing. There were no significant differences among warm-up activities on impulse.

The effect of warm-up activity on GRF_v variables was analyzed using a multivariate analysis of variance (MANOVA), with the independent variable being the warm-up activity. The dependent variables were the GRF_v variables (peak forefoot magnitude, peak rearfoot magnitude, forefoot rate of loading, rearfoot rate of loading, impulse). This model also was blocked for subject in order to make this model a within-subject test. In checking for assumptions, the rearfoot rate of loading variable indicated an inequality of variance. Thus, a log transformation was performed on this variable in order to meet this assumption and was included in the final statistical model. The detailed

statistical analysis is shown in Appendix C, and the levels of significance for all response variables can be found in Table 3.

This analysis indicated that peak forefoot magnitude (F1), peak rearfoot magnitude (F2), and forefoot rate of loading (F1LR) produced significantly different results among warm-up activities ($p < 0.05$). Rearfoot rate of loading (F2LR) and impulse did not demonstrate statistical significance.

Following this MANOVA, a Tukey post-hoc test of least square means was completed in order to determine where the differences among activities were for each GRF_v variable. This analysis is detailed in Table 4. For peak forefoot magnitude, the mean value was significantly greater for the dynamic warm-up (2204.24 N) when compared to the control (2010.15 N) and passive stretch (1906.23 N) activities. However, there was not a significant difference in least square means between the control and passive stretch activities. Peak rearfoot magnitude and forefoot rate of loading indicated similar results, where the dynamic warm-up (894.95 N, 39704.97 N/s) was significantly greater than the control (836.95 N, 35021 N/s) and passive stretching activities (823.31 N, 32875.84 N). However, again the control and passive stretching activities were not significantly different from each other. As seen in the whole model MANOVA, Rearfoot rate of loading and impulse failed to reach a significant difference among warm-up activities.

Table 3

Tukey Post Hoc comparison of warm-up activities. Levels not connected by the same letter are significantly different from each other.

GRF _v Variable	Condition	Least Square Mean
F1	Dynamic A	2122.45
	Control B	1928.35
	Passive Stretch B	1824.44
F2	Dynamic A	861.76
	Control B	803.77
	Passive Stretch B	790.12
F1LR	Dynamic A	38128.18
	Control B	33445.13
	Passive Stretch B	31299.05
Log F2LR	Dynamic A	3.52
	Control A	3.48
	Passive Stretch A	3.45
Impulse	Dynamic A	170.92
	Control A	167.15
	Passive Stretch A	166.77

Discussion

In this study, the type of warm-up activity prior to a jump landing significantly affected three out of five GRF_v variables (peak forefoot magnitude, peak rearfoot magnitude, and forefoot rate of loading). An analysis of the peak forefoot magnitude (F1) variable indicated that the dynamic warm-up generated a significantly greater peak forefoot landing force (2204.24 N) than the control (2010.15 N) and passive stretching (1906.23 N) activities. This finding partially supports Hypothesis 1 of this study, which stated that the dynamic warm-up would result in the highest F1 magnitude. However, this hypothesis also stated that the control would show a higher F1 magnitude than the passive stretching warm-up. While the F1 magnitude for the control was greater than the passive stretching warm-up, these results were not significant. This indicated that the

passive stretching warm-up used in this study was not effective in decreasing peak forefoot GRF_v during a jump landing.

An analysis of the peak rearfoot magnitude (F2) demonstrated similar findings. The dynamic warm-up had a significantly higher F2 magnitude (894.95 N) compared to the passive stretching (823.31 N) and control activities (836.95 N), which partially supports Hypothesis 2 of this study. Again, the passive stretching warm-up and control condition yielded similar results and were not significantly different from each other. The differences in peak GRF_v between the dynamic warm-up and other activities may be due to an increase in muscular stiffness in the lower extremities as a result of a higher level of motor unit activation (Bosco et al., 1982). However, the lack of differences in F1 and F2 between the passive stretching and control activities are surprising, since previous research has shown that a passive stretching warm-up can reduce muscular stiffness (Behm et al., 2004, Kay & Blazevich, 2008). This reduction should have been reflected by decreases in forefoot and rearfoot peak magnitudes and rates of loading.

The dynamic warm-up also produced a significantly higher forefoot rate of loading (F1LR, 39704.97 N/s) compared to the passive stretching (32875.84 N/s) and control (35021.93 N/s) activities. This demonstrates that a dynamic warm-up may be useful in recruiting motor units prior to performing a similar activity. In other words, the warm-up prepared the central nervous system to perform a jumping activity. This is reflected by the higher rate of loading because it indicates an increase in muscular stiffness, which is necessary for an individual to perform an effective jump (Bradley et al., 2007; Horita et al., 2002). Thus, the effects of the dynamic warm-up on participants' F1LR partially support Hypothesis 3 of this study. However, this hypothesis also

postulated that the passive stretching warm-up would produce significantly lower values than the control condition, which the results of this study do not support.

The rearfoot rate of loading (F2LR) did not yield any differences among activities. This did not support the Hypothesis 4 of this study, which stated that the dynamic warm-up would have the highest rearfoot rate of loading, followed by the control condition, and that the passive stretching warm-up would have the lower rearfoot rate of loading. One possible explanation as to why these results occurred is that the rearfoot rate of loading was the only variable of the five that did not meet the equality of variance assumption. This could indicate that the participants of this study had different landing patterns, with some landing with more rearfoot force than others. While a log transformation allowed for this variable to meet this assumption, there was still not a statistically significant difference among activities. Another possible reason as to why F2LR was not different among activities is because the initial forefoot strike may have already activated the muscles that control dorsiflexion. Therefore, the mere action of landing from a jump may have activated those muscles before the heel strike occurred. Additionally, F2LR values were higher for the passive stretching and dynamic warm-up activities compared to the control condition (see Figure 8). Again, while the results were not significant, this supports the notion that this particular passive stretching warm-up was not effective in decreasing muscular stiffness prior to a jumping activity.

Finally, impulse did not show a statistically significant difference among warm-up activities. This does not support Hypothesis 5 of this study. However, despite failing to reach significance, the passive stretching warm-up did elicit the highest impulse of the three warm-ups (see Figure 9). These results indicate that while the passive stretching

warm-up demonstrated the lowest peak forefoot and rearfoot GRF_v magnitude and forefoot rate of loading, it still produced a greater force applied over time. Therefore, after a passive stretching warm-up, a person landing from a jump has more momentum to overcome in order to provide a quick, explosive second jump. Also, impulse for the dynamic warm-up and control activities were almost identical, which demonstrated that the dynamic warm-up was not effective in decreasing impulse and limiting momentum. This is surprising, given that previous literature has discussed an inverse relationship between muscular stiffness and impulse (Enoka, 2008).

These findings have multiple implications. For one, it seems that the dynamic warm-up that was prescribed for this study was effective in increasing muscular stiffness in the lower extremities. This can be observed through the increases in F1, F2, and F1LR after the dynamic warm-up compared to the other warm-up activities. Thus, an athlete who is seeking to maximize jumping performance may want to consider a dynamic warm-up that utilizes the stretch-shorten cycle prior to an activity. This relationship between increased muscular stiffness and jumping performance has been shown to occur in previous studies (Bradley et al., 2007; Horita et al., 2002). However, an increase in muscular stiffness may cause an increase in excessive loading rates and shock (Butler, Crowell, & Davis, 2003). While athletes who have a higher bone mineral density may be able to tolerate these loading rates, a person who exercises infrequently may be at risk for injuries to bones and joints.

The results of this study also indicated that the passive stretching warm-up that was prescribed was ineffective in decreasing muscular stiffness. This is observed through the failure of the passive stretching warm-up to significantly decrease F1, F2, F1LR, and

F2LR and increase impulse compared to the control condition. These results are surprising, since previous literature has described the ability of a passive stretching warm-up to decrease muscular activation, and therefore muscular stiffness (Behm et al., 2004; Behm et al., 2001; Kay & Blazevich, 2008). However, while the failure of the passive stretching warm-up to achieve significance may have been affected by the high standard error, it was marginally effective in decreasing F1, F2, and F1LR, and increasing impulse when compared to the control condition. Also, as stated previously, the F2LR variable for the passive stretching warm-up was marginally higher than the control, which could mean that this warm-up was completely ineffective in limiting the magnitude of F2LR. Therefore, the inter-trial variability within participants may have caused the passive stretching warm-up to fail to reach significance among all variables (F1, F2, F1LR, F2LR, impulse). Thus, while the results of this study indicated that a dynamic warm-up may be effective in increasing muscular activation in the lower extremities, they also show that a passive stretching warm-up may be ineffective in decreasing muscular activation.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of this study was to examine the effects of warm-up activities on vertical ground reaction forces (GRF_v) during jump landings. A passive stretching warm-up, a dynamic warm-up, and a no warm-up control were the activities tested, and a drop jump was used to simulate a jump landing. Peak forefoot magnitude (F1), rearfoot magnitude (F2), forefoot rate of loading (F1LR), rearfoot rate of loading (F2LR), and impulse were the dependent measures used to examine the effects of each warm-up activity on landing forces.

Summary

Twenty participants (8 women and 12 men, 22.6 years old $\pm$ 1.82) volunteered for this study. GRF_v data was collected during a jump landing after completing each warm-up activity. One activity, a passive stretching warm-up, consisted of stretching exercises on the hip extensors and plantar flexors. These stretches lasted for a duration of 30 seconds, and were completed twice on each leg. Another activity, a dynamic warm-up, was comprised of high knees, skips, and shuttle run exercises. These exercises were performed over a 20 meter segment. Each exercise was completed in order, and then repeated twice for a total of three repetitions, with 10 to 15 seconds of rest between each repetition. The third activity was a control condition, which did not involve a warm-up activity. Instead, participants simply arrived for testing and immediately performed eight drop jump landings. These activities were completed in a counterbalanced order.

Following completion of both the dynamic and passive stretching warm-ups, participants were asked to step off of a 37 cm box and land bilaterally on the floor, with their dominant foot on the force platform and their non-dominant foot off to the side of it. GRF_v data was sampled at 1000 Hz, and participants were asked to complete this jump landing eight times following each warm-up condition. This GRF_v data was analyzed by collecting data on five separate variables of the GRF_v curve: the peak GRF_v magnitude for the forefoot and rearfoot, the rate of loading to each of these peaks, and the integrated area under GRF_v curve.

The means of all variables (F1, F2, F1LR, F2LR, impulse) for the eight jump landing trials after each activity were calculated, and were analyzed using a multivariate analysis of variance (MANOVA). The level of significance was set at 0.05, and the effect of each activity was further analyzed using a Tukey post hoc comparison test.

Conclusions

The conclusions drawn based on the hypothesis that were postulated are:

1. A dynamic warm-up prior to a jumping activity seems to increase muscular stiffness in the lower extremities. This was determined through the data collected in this study by a higher F1, F2, and F1LR for the dynamic warm-up relative to the control (no warm-up) activity. This could be a beneficial warm-up to athletes who are seeking to increase jumping performance. Also, through increasing muscular stiffness, this warm-up could place an athlete more at risk for injuries to bones and joints in the lower limbs, since previous literature has indicated that muscular stiffness can directly affect the overall stiffness of the leg (Butler, Crowell, & Davis, 2003). However, there are many other factors that affect leg

stiffness, and therefore the results of this study do not directly indicate whether a person with higher muscular stiffness in the lower extremities is at a greater risk for bony injuries. Furthermore, F2LR and impulse were not significantly different among the warm-up activities. These similarities could indicate a difference in participants' landing strategies from trial to trial.

2. The passive stretching warm-up used in this study was not effective in decreasing muscular stiffness in the legs. When compared to the control condition, this warm-up activity exhibited no statistically significant differences among any of the five GRF_v variables. This indicates that the passive stretching warm-up protocol used in this study has no effect on injury or performance.

Recommendations for Future Studies

This study examined the effects of different warm-up activities on GRF_v during jump landings. The neuromuscular response to warm-ups requires further research. Some possible future research could include:

1. This study examined recreational basketball players. However, since previous research has noted that landing strategies differ among athletes in various sports (Cowley et al., 2006) and experience levels (McKinley & Pedotti, 1992) differ, future studies should investigate the effects of warm-up activities among individuals of different skill levels and sports.
2. As previously noted, the passive stretching warm-up was not effective in significantly altering any of the GRF_v variables (peak forefoot and rearfoot GRF_v magnitude, peak forefoot and rearfoot rate of loading, and impulse). It is possible that the duration or specificity of this protocol was not sufficient, and thus future

studies could incorporate a passive stretching protocol that uses stretches of a longer duration or different type.

3. All data was collected in the morning in order to minimize the amount of muscular stiffness in the lower limbs that occurs as a result of performing daily living activities. Therefore, it can be argued that the control condition reflected participants' lower extremity muscular stiffness at a near minimum when data collection occurred, and therefore the differences in landing forces between the passive stretching warm-up and control failed to reach significance. Perhaps future studies could investigate the effects of stretching at a later point in the day, since it could decrease muscular stiffness in the lower extremities after daily living activities have been performed.
4. A study that combined a kinematic analysis with kinetic GRF_v data could help elucidate the results of this study. For example, differences in landing forces could be due to changes in angular displacement and velocity at the ankle, knee, and hip joints. Furthermore, combining kinematic and kinetic data could allow for stiffness in the lower extremities to be quantified using calculations for stiffness that have been previously described, such as one noted by McMahon and Cheng (1990).
5. This study did not investigate the changes in contributions from individual muscles in controlling segmental motion during landing. Thus, future studies could incorporate the use of electromyography to determine if the warm-up activities used in this study alter the activation timing and magnitude of the

plantar flexors and hip extensors, which could also help to explain the results that were shown by this study.

6. This study did not collect data on jumping performance following the drop jump landing. Therefore, future studies could also collect jumping performance data along with GRF_v data. Inclusion of this variable in the study design would allow for researchers to connect jumping height with changes in GRF_v , making the results more applicable to performance enhancement.

Implications

This study adds to the growing body of research performed in the areas of athletic performance, injury prevention, neuromechanics of the lower limbs, and exercise prescription. It seems that a dynamic warm-up is effective in increasing certain components of GRF_v during a jump landing, which could increase jumping performance for basketball players. Therefore, a basketball player may want to utilize a dynamic warm-up prior to engaging in athletic competition. Also, while the scope of this study does not encompass making recommendations for injury prevention, previous studies have made connections between muscular stiffness and leg stiffness (Cook & McDonagh, 1995; Johns & Wright, 1962; Watkins, 1999). Therefore, while the changes in muscular stiffness among the different warm-up conditions in this study may reflect a change in the overall stiffness of the leg system and may have implications for injury prevention, leg stiffness was not quantified in this study. Thus, the results of this study cannot provide a recommendation for reducing the incidence of injury during a jumping activity.

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APPENDIX A
HUMAN SUBJECT INFORMED CONSENT FORM

INFORMED CONSENT TO PARTICIPATE IN:

The Effects of Altering Muscular Stiffness on Vertical Ground Reaction Forces During Jump Landings

A research project on the effects of warm-up conditions on muscular stiffness and its implications for vertical ground reaction forces during jump landings is being conducted by Jacob Hinkel-Lipsker in the Department of Kinesiology at Cal Poly, San Luis Obispo.

The purpose of the study is to examine how different warm-up conditions affect vertical ground reaction forces in jump landings. You are being asked to take part in this study by performing three warm-up conditions on separate days. One condition is a passive stretching warm-up, where different muscles in your legs will be stretched according to a specific protocol. Another condition, a dynamic warm-up, will involve low-to-moderate intensity ballistic activities such as running and jumping. The third condition is a no warm-up condition that will act as a control for this experiment.

After completing each warm-up condition, you will be asked to step off of a 40 cm high box and land on a force platform, which is built into the ground and is flush with the floor. This is meant to simulate a jump landing. You will complete five trials of this for after each warm-up condition. Upon landing from stepping off of the box, the ground reaction forces that are applied to your lower extremities in a vertical direction will be interpreted through software. In examining different elements of the ground reaction forces in graphical and numeric format, conclusions will be made regarding how the different warm-up conditions affected muscular stiffness in your lower extremities.

Your participation will involve 3 sessions, and will take approximately 30 minutes per session. Please be aware that you are not required to participate in this research and you may discontinue your participation at any time without penalty.

The possible risks associated with participation in this study include injury to the hips, knees, or ankles during landing after stepping off of the box and any inherent risks involved in low-to-moderate intensity exercise from the dynamic warm-up. If you should experience physical discomfort or injury and you are a Cal Poly student, please be aware that you may contact the Health Center at 756-1211 for assistance. If you are not a Cal Poly student, please contact your personal physician for assistance.

Your confidentiality will be protected and no information besides numerical data will be referred to in the materials of this study. Your name will not be associated with the data collected. Potential benefits associated with the study include the knowledge that you will be contributing to research in the area of abdominal exercise and a greater awareness of how to complete a specific warm-up in your future athletic endeavors.

If you have questions regarding this study or would like to be informed of the results when the study is completed, please feel free to contact Dr. Robert Clark at 756-0285. If you have concerns regarding the manner in which the study is conducted, you may contact Dr. Steve Davis, Chair of the Cal Poly Human Subjects Committee, at (805) 756-2754, sdavis@calpoly.edu, or Dr. Susan Opava, Dean of Research and Graduate Programs, at (805) 756-1508, sopava@calpoly.edu.

If you agree to voluntarily participate in this research project as described, please indicate your agreement by signing below. Please keep one copy of this form for your reference, and thank you for your participation in this research.

_____	_____
Signature of Volunteer	Date

_____	_____
Signature of Researcher	Date

APPENDIX B

PAR-Q

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
☐	☐	2. Do you feel pain in your chest when you do physical activity?
☐	☐	3. In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
☐	☐	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
☐	☐	7. Do you know of <u>any other reason</u> why you should not do physical activity?

If
you
answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT _____
or GUARDIAN (for participants under the age of majority)

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

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APPENDIX C
STATISTICS OUTPUT

MANOVA

Manova Fit

Response Specification

To construct the linear combinations across responses,

Choose Response ▾

☐ Univariate Tests Also

☒ Test Each Column Separately Also

N 60
DFE 38

Least Squares Means

Overall Means

Overall Means					
	F1	F2	F1LR	logf2lr	Impulse
	2040.20317	851.737667	35867.578	3.51827884	171.0495

Condition

Condition	F1	F2	F1LR	logf2lr	Impulse
Control	2010.146	836.953	35021.9245	3.48472472	169.541
Dynamic	2204.237	894.9495	39704.9695	3.55640967	169.9225
Passive Stretch	1906.2265	823.3105	32875.84	3.51370213	173.685

Identity**M Matrix**

M

	F1	F2	F1LR	logf2lr	Impulse
	1	0	0	0	0
	0	1	0	0	0
	0	0	1	0	0
	0	0	0	1	0
	0	0	0	0	1

Whole Model

Test	Value	Approx. F	NumDF	DenDF	Prob>F
Wilks' Lambda	4.8633e-5	10.7839	105	170.97	<.0001*
Pillai's Trace	4.0174411	7.3987	105	190	<.0001*
Hotelling-Lawley	53.456124	16.5847	105	113.09	<.0001*
Roy's Max Root	35.052165	63.4277	21	38	<.0001*

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	2493.7311	16957.372	5	34	<.0001*

Subject

Test	Value	Approx. F	NumDF	DenDF	Prob>F
Wilks' Lambda	6.0183e-5	11.3981	95	170.03	<.0001*
Pillai's Trace	3.9621807	7.6356	95	190	<.0001*
Hotelling-Lawley	51.972167	17.8275	95	111.06	<.0001*
Roy's Max Root	34.542277	69.0846	19	38	<.0001*

Condition

Test	Value	Approx. F	NumDF	DenDF	Prob>F
Wilks' Lambda	0.3789912	4.2457	10	68	0.0001*
Pillai's Trace	0.6796107	3.6029	10	70	0.0007*
Hotelling-Lawley	1.4839573	4.9537	10	48.328	<.0001*
Roy's Max Root	1.3711895	9.5983	5	35	<.0001*

Column1

Column1

M Matrix

M

F1	F2	F1LR	logf2lr	Impulse
1	0	0	0	0

Whole Model

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	19.28058	34.8887	21	38	<.0001*

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	266.96352	10144.614	1	38	<.0001*

Subject

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	18.302279	36.6046	19	38	<.0001*

Condition

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.978301	18.5877	2	38	<.0001*

Column2

Column2

M Matrix

M

F1	F2	F1LR	logf2lr	Impulse
0	1	0	0	0

Whole Model

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	13.913773	25.1773	21	38	<.0001*

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	256.04367	9729.6596	1	38	<.0001*

Subject

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	13.573307	27.1466	19	38	<.0001*

Condition

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.340465	6.4688	2	38	0.0038*

Column3

Column3

M Matrix

M	F1	F2	F1LR	logf2lr	Impulse
	0	0	1	0	0

Whole Model

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	12.237415	22.1439	21	38	<.0001*

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	140.18013	5326.8451	1	38	<.0001*

Subject

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	11.351495	22.7030	19	38	<.0001*

Condition

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.8859195	16.8325	2	38	<.0001*

Column4

Column4

M Matrix

M	F1	F2	F1LR	logf2lr	Impulse
	0	0	0	1	0

Whole Model

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	4.630944	8.3798	21	38	<.0001*

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	679.455	25819.290	1	38	<.0001*

Subject

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	4.5833576	9.1667	19	38	<.0001*

Condition

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.0475865	0.9041	2	38	0.4134

Column5

Column5

M Matrix

M	F1	F2	F1LR	logf2lr	Impulse
	0	0	0	0	1

Whole Model

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	11.947779	21.6198	21	38	<.0001*

Intercept

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	1024.4789	38930.198	1	38	<.0001*

Subject

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	11.825323	23.6506	19	38	<.0001*

Condition

Test	Value	Exact F	NumDF	DenDF	Prob>F
F Test	0.1224555	2.3267	2	38	0.1114

F1

Fit Group**Response F1****Whole Model****Actual by Predicted Plot** **Summary of Fit**

RSquare	0.94931
RSquare Adj	0.946594
Root Mean Square Error	156.903
Mean of Response	2040.203
Observations (or Sum Wgts)	60

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob> t
Intercept	1958.4121	84.98701	18	23.04	<.0001*
Condition[Control]	-30.05717	28.64644	38	-1.05	0.3007
Condition[Dynamic]	164.03383	28.64644	38	5.73	<.0001*
Gender[F]	-408.9554	84.98701	18	-4.81	0.0001*

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Pct of Total
Subject[Gender]	5.2997187	130471.42	46264.189	39795.276	221147.56	84.126
Residual		24618.556	5647.884	16442.509	40890.174	15.874
Total		155089.98	46378.961	93105.465	308615.43	100.000

-2 LogLikelihood = 791.28012714

Note: Total is the sum of the positive variance components.

Total including negative estimates = 155089.98

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	2	2	38	18.5877	<.0001*
Gender	1	1	18	23.1551	0.0001*

Residual by Predicted Plot

Condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Control	1928.3549	89.685063
Dynamic	2122.4459	89.685063
Passive Stretch	1824.4354	89.685063

LS Means Plot

LSMeans Differences Tukey HSD

$\alpha = 0.050$

		LSMean[j]		
LSMean[i]	Mean[i]-Mean[j]	Control	Dynamic	Passive Stretch
	Std Err Dif			
	Lower CL Dif			
	Upper CL Dif			
	Control	0	-194.09	103.919
		0	49.6171	49.6171
		0	-315.1	-17.088
		0	-73.084	224.927
	Dynamic	194.091	0	298.011
		49.6171	0	49.6171
		73.0835	0	177.003
		315.098	0	419.018
	Passive Stretch	-103.92	-298.01	0
		49.6171	49.6171	0
		-224.93	-419.02	0
		17.088	-177	0

Level		Least Sq Mean
Dynamic	A	2122.4459
Control	B	1928.3549
Passive Stretch	B	1824.4354

Levels not connected by same letter are significantly different.

F2

Response F2

Whole Model

Actual by Predicted Plot

Summary of Fit

RSquare	0.929403
RSquare Adj	0.925621
Root Mean Square Error	66.8856
Mean of Response	851.7377
Observations (or Sum Wgts)	60

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob> t
Intercept	818.55097	26.37991	18	31.03	<.0001*
Condition[Control]	-14.78467	12.21158	38	-1.21	0.2335
Condition[Dynamic]	43.211833	12.21158	38	3.54	0.0011*
Gender[F]	-165.9335	26.37991	18	-6.29	<.0001*

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Pct of Total
Subject[Gender]	2.6533035	11870.042	4466.8767	3115.1242	20624.959	72.628
Residual		4473.6841	1026.3335	2987.9328	7430.5625	27.372
Total		16343.726	4506.008	10161.413	30562.129	100.000

-2 LogLikelihood = 684.36292525

Note: Total is the sum of the positive variance components.

Total including negative estimates = 16343.726

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	2	2	38	6.4688	0.0038*
Gender	1	1	18	39.5659	<.0001*

Residual by Predicted Plot

Condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Control	803.76631	29.069267
Dynamic	861.76281	29.069267
Passive Stretch	790.12381	29.069267

LSMeans Differences Tukey HSD

$\alpha = 0.050$

		LSMean[j]		
LSMean[i]	Mean[i]-Mean[j]	Control	Dynamic	Passive Stretch
	Std Err Dif			
	Lower CL Dif			
	Upper CL Dif			
	Control	0	<u>-57.997</u>	13.6425
		0	<u>21.1511</u>	21.1511
		0	<u>-109.58</u>	-37.941
		0	<u>-6.4127</u>	65.2263
	Dynamic	<u>57.9965</u>	0	<u>71.639</u>
		<u>21.1511</u>	0	<u>21.1511</u>
		<u>6.41267</u>	0	<u>20.0552</u>
		<u>109.58</u>	0	<u>123.223</u>
	Passive Stretch	-13.642	<u>-71.639</u>	0
		21.1511	<u>21.1511</u>	0
		-65.226	<u>-123.22</u>	0
		37.9413	<u>-20.055</u>	0

Level		Least Sq Mean
Dynamic	A	861.76281
Control	B	803.76631
Passive Stretch	B	790.12381

Levels not connected by same letter are significantly different.

F1LR

Response F1LR

Whole Model

Actual by Predicted Plot

Summary of Fit

RSquare	0.920961
RSquare Adj	0.916727
Root Mean Square Error	3806.647
Mean of Response	35867.58
Observations (or Sum Wgts)	60

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob> t
Intercept	34290.784	1604.862	18	21.37	<.0001*
Condition[Control]	-845.6535	694.9955	38	-1.22	0.2312
Condition[Dynamic]	3837.3915	694.9955	38	5.52	<.0001*
Gender[F]	-7883.968	1604.862	18	-4.91	0.0001*

REML Variance Component Estimates

Random Effect	Var Ratio	Component	Std Error	95% Lower	95% Upper	Pct of Total
Subject[Gender]	3.0793134	44620987	16520930	12240560	77001415	75.486
Residual		14490564	3324363.3	9678115.6	24068092	24.514
Total		59111551	16632045	36438086	112199573	100.000

-2 LogLikelihood = 1139.4133285

Note: Total is the sum of the positive variance components.

Total including negative estimates = 59111551

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	2	2	38	16.8325	<.0001*
Gender	1	1	18	24.1332	0.0001*

Residual by Predicted Plot

Condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Control	33445.131	1748.8856
Dynamic	38128.176	1748.8856
Passive Stretch	31299.046	1748.8856

LSMeans Differences Tukey HSD

$\alpha = 0.050$

		LSMean[j]		
LSMean[i]	Mean[i]-Mean[j]	Control	Dynamic	Passive Stretch
	Std Err Dif			
	Lower CL Dif			
	Upper CL Dif			
	Control	0	<u>-4683</u>	2146.08
		0	<u>1203.77</u>	1203.77
		0	<u>-7618.8</u>	-789.7
		0	<u>-1747.3</u>	5081.86
	Dynamic	<u>4683.05</u>	0	<u>6829.13</u>
		<u>1203.77</u>	0	<u>1203.77</u>
		<u>1747.26</u>	0	<u>3893.35</u>
		<u>7618.83</u>	0	<u>9764.91</u>
	Passive Stretch	-2146.1	<u>-6829.1</u>	0
		1203.77	<u>1203.77</u>	0
		-5081.9	<u>-9764.9</u>	0
		789.696	<u>-3893.3</u>	0

Level		Least Sq Mean
Dynamic	A	38128.176
Control	B	33445.131
Passive Stretch	B	31299.046

Levels not connected by same letter are significantly different.

F2LR, logged

Response logf2lr

Summary of Fit

RSquare	0.808281
RSquare Adj	0.79801
Root Mean Square Error	0.169603
Mean of Response	3.518279
Observations (or Sum Wgts)	60

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob> t
Intercept	3.481695	0.054528	18	63.85	<.0001*
Condition[Control]	-0.033554	0.030965	38	-1.08	0.2854
Condition[Dynamic]	0.0381308	0.030965	38	1.23	0.2257
Gender[F]	-0.182919	0.054528	18	-3.35	0.0035*

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Pct of Total
Subject[Gender]	1.651256	0.0474987	0.0191558	0.0099541	0.0850433	62.282
Residual		0.0287652	0.0065992	0.019212	0.0477775	37.718
Total		0.0762639	0.019531	0.0488586	0.1355255	100.000

-2 LogLikelihood = 7.5505250589

Note: Total is the sum of the positive variance components.

Total including negative estimates = 0.0762639

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	2	2	38	0.9041	0.4134
Gender	1	1	18	11.2533	0.0035*

Residual by Predicted Plot

Least Squares Means Table

Level	Least Sq Mean	Std Error
Control	3.4481409	0.06270668
Dynamic	3.5198258	0.06270668
Passive Stretch	3.4771183	0.06270668

LSMeans Differences Tukey HSD

$\alpha = 0.050$

		LSMean[j]		
LSMean[i]	Mean[i]-Mean[j]	Control	Dynamic	Passive Stretch
	Std Err Dif			
	Lower CL Dif			
	Upper CL Dif			
	Control	0	-0.0717	-0.029
		0	0.05363	0.05363
		0	-0.2025	-0.1598
		0	0.05912	0.10182
	Dynamic	0.07168	0	0.04271
		0.05363	0	0.05363
		-0.0591	0	-0.0881
		0.20249	0	0.17351
	Passive Stretch	0.02898	-0.0427	0
		0.05363	0.05363	0
		-0.1018	-0.1735	0
		0.15978	0.08809	0

Level		Least Sq Mean
Dynamic	A	3.5198258
Passive Stretch	A	3.4771183
Control	A	3.4481409

Levels not connected by same letter are significantly different.

Impulse

Response Impulse

Whole Model

Actual by Predicted Plot

Summary of Fit

RSquare	0.91955
RSquare Adj	0.91524
Root Mean Square Error	6.715125
Mean of Response	171.0495
Observations (or Sum Wgts)	60

Parameter Estimates

Term	Estimate	Std Error	DFDen	t Ratio	Prob> t
Intercept	168.28174	2.983996	18	56.39	<.0001*
Condition[Control]	-1.5085	1.226009	38	-1.23	0.2261
Condition[Dynamic]	-1.127	1.226009	38	-0.92	0.3638
Gender[F]	-13.83882	2.983996	18	-4.64	0.0002*

REML Variance Component Estimates

Random Effect	Var Ratio	Component	Var	Std Error	95% Lower	95% Upper	Pct of Total
Subject[Gender]	3.457978	155.93029	57.091323	44.033354	267.82723	77.568	
Residual		45.09291	10.345023	30.117144	74.897038	22.432	
Total		201.0232	57.402895	123.13796	385.82102	100.000	

-2 LogLikelihood = 431.21149747

Note: Total is the sum of the positive variance components.

Total including negative estimates = 201.0232

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	2	2	38	2.3267	0.1114
Gender	1	1	18	21.5081	0.0002*

Residual by Predicted Plot

Condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Control	166.77324	3.2260393
Dynamic	167.15474	3.2260393
Passive Stretch	170.91724	3.2260393

LSMeans Differences Tukey HSD

$\alpha = 0.050$

		LSMean[j]		
LSMean[i]	Mean[i]-Mean[j]	Control	Dynamic	Passive Stretch
	Std Err Dif			
	Lower CL Dif			
	Upper CL Dif			
	Control	0	-0.3815	-4.144
		0	2.12351	2.12351
		0	-5.5604	-9.3229
		0	4.79737	1.03487
	Dynamic	0.3815	0	-3.7625
		2.12351	0	2.12351
		-4.7974	0	-8.9414
		5.56037	0	1.41637
	Passive Stretch	4.144	3.7625	0
		2.12351	2.12351	0
		-1.0349	-1.4164	0
		9.32287	8.94137	0

Level	Least Sq Mean
Passive Stretch A	170.91724
Dynamic A	167.15474
Control A	166.77324

Levels not connected by same letter are significantly different.

Discriminant Analysis

Discriminant Analysis

Discriminant Method: Linear

Canonical Plot

Eigenvalue	Percent	Cum Percent	Canonical Corr	Likelihood Ratio	Approx. F	NumDF	DenDF	Prob>F
1.37118951	92.4009	92.4009	0.76044115	0.37899125	6.6183	10	106	<.0001*
0.11276781	7.5991	100.0000	0.31833933	0.89866007	1.5224	4	54	0.2087

Test	Value	Approx. F	NumDF	DenDF	Prob>F
Wilks' Lambda	0.3789912	6.6183	10	106	<.0001*
Pillai's Trace	0.6796107	5.5588	10	108	<.0001*
Hotelling-Lawley	1.4839573	7.7705	10	76.8	<.0001*
Roy's Max Root	1.3711895	14.8088	5	54	<.0001*

► Within Matrix

► Between Matrix

► Scoring Coefficients

► Standardized Scoring Coefficients

APPENDIX D
SUMMARY DATA

Subject	Condition	Gender	F1	F2	F1LR	F2LR	Impulse
1	Control	M	1910.60	992.48	40955.50	9245.71	169.51
1	Dynamic	M	2009.18	1048.69	38168.88	4577.26	184.03
1	Passive Stretch	M	2014.24	1043.65	40755.75	7130.23	183.76
2	Control	F	1537.11	814.00	24779.88	2498.97	156.54
2	Dynamic	F	1789.89	927.52	30966.50	5476.36	159.25
2	Passive Stretch	F	1820.38	914.99	31744.25	3293.68	171.19
3	Control	M	1979.10	980.42	33018.63	3472.13	189.91
3	Dynamic	M	2471.01	1151.80	51331.88	10066.46	198.22
3	Passive Stretch	M	1954.81	1092.96	40093.00	8884.84	190.05
4	Control	M	2248.40	1041.62	47999.88	6271.91	181.52
4	Dynamic	M	2284.44	1027.48	48364.13	10966.20	165.48
4	Passive Stretch	M	2104.38	1013.60	48763.00	11879.16	165.93
5	Control	F	1189.86	424.02	19563.13	1458.76	136.05
5	Dynamic	F	1590.36	504.52	26140.75	1579.70	145.74
5	Passive Stretch	F	1461.15	332.15	23886.38	1700.39	154.07
6	Control	M	1677.44	749.38	27869.00	1533.34	181.13
6	Dynamic	M	1932.48	864.76	34143.75	2577.80	181.55
6	Passive Stretch	M	1391.74	890.34	22639.63	817.80	176.01
7	Control	M	1991.15	961.18	38840.75	8279.05	168.26
7	Dynamic	M	2049.58	991.87	43206.63	8937.71	168.54
7	Passive Stretch	M	1814.01	973.25	32550.88	7146.31	167.93
8	Control	F	1139.17	702.88	18445.63	2440.08	143.75
8	Dynamic	F	1151.72	746.30	16746.00	3301.60	139.09
8	Passive Stretch	F	1204.94	680.62	19296.00	2503.44	128.46
9	Control	F	1181.60	734.69	19307.75	1362.49	144.70
9	Dynamic	F	1537.94	619.50	22404.50	1353.52	131.66
9	Passive Stretch	F	946.38	582.09	14917.38	1238.03	139.38
10	Control	F	1747.21	675.72	37454.13	908.33	152.08
10	Dynamic	F	2460.48	593.92	47213.75	2109.33	158.58
10	Passive Stretch	F	1736.63	669.98	28014.38	924.26	158.56

Subject	Condition	Gender	F1	F2	F1LR	F2LR	Impulse
11	Control	F	1865.76	788.99	32334.50	3133.60	168.44
11	Dynamic	F	2113.64	764.45	35896.25	5455.50	163.75
11	Passive Stretch	F	1752.18	699.65	28710.50	2134.44	175.65
12	Control	M	2769.91	840.33	51204.75	6999.64	168.20
12	Dynamic	M	2896.28	897.21	56280.13	7309.25	159.91
12	Passive Stretch	M	2390.26	785.80	38855.50	6683.30	166.37
13	Control	M	2720.50	985.50	46785.75	1700.25	176.50
13	Dynamic	M	2745.15	1005.48	49551.38	1804.50	174.25
13	Passive Stretch	M	2467.75	900.25	37895.25	1568.50	183.75
14	Control	M	2182.74	1039.86	33659.50	2310.91	217.29
14	Dynamic	M	2254.58	1069.36	41274.00	2285.12	212.36
14	Passive Stretch	M	2099.10	1148.22	38196.00	4234.24	209.11
15	Control	M	2948.25	891.33	44665.75	4725.20	195.65
15	Dynamic	M	3166.50	1015.75	51042.00	5871.75	184.25
15	Passive Stretch	M	2955.50	915.38	42357.50	5230.25	191.50
16	Control	F	1352.48	521.50	21440.50	1356.50	151.03
16	Dynamic	F	1398.10	525.65	24600.48	2080.25	155.48
16	Passive Stretch	F	1106.75	487.38	19701.15	1374.13	167.85
17	Control	M	2568.00	1122.75	39870.13	9865.25	176.07
17	Dynamic	M	2786.25	1234.20	41996.13	1383.13	171.50
17	Passive Stretch	M	2435.13	890.50	34790.15	8762.38	181.45
18	Control	M	2564.74	785.41	37641.45	2645.68	166.50
18	Dynamic	M	2622.35	966.35	41456.25	2986.50	186.14
18	Passive Stretch	M	2546.75	871.50	34609.87	3451.50	184.00
19	Control	F	1642.15	641.15	26789.13	1704.50	156.15
19	Dynamic	F	1780.13	698.50	33545.50	2256.15	171.05
19	Passive Stretch	F	1680.95	612.65	29865.18	1890.22	178.13
20	Control	M	2986.75	1045.85	57812.75	7156.75	191.54
20	Dynamic	M	3044.68	1245.68	59770.50	7560.13	187.62
20	Passive Stretch	M	2241.50	961.25	49875.05	6843.13	200.55