The 2-dimensional biomechanical modeling of the loads on the spine (L5-L1) during a “Back Walkover” maneuver in gymnastics

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Final thesis, 15 credits

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Acknowledge
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I wish to thank the University of Adelaide and the personnel there for letting me use their sports engineering lab equipment and for giving me encouragement and advice. Also I would like to give thanks for the advising received from Halmstad University.
Abstract

Injuries in the female gymnast are common and it is important to understand the biomechanical factors responsible for injury. The Back Walkover maneuver requires one of the greatest amounts of lumbar hyperextension compared to other common gymnastic maneuvers. During the Back Walkover large lateral and vertical impact forces follow on the spine. The spine and muscles around the spine have to absorb generally large forces; therefore the loads on the back and certainly on the lower back are of significant interest. Additionally, it takes a lot of strength and a vast range of motion to perform gymnastic maneuvers such as The Back Walkover. It is of interest to study mechanical loads on a female gymnast since they show higher occurrences of stress-related pathologies of the lumbar spine.

Therefore the purpose of this project was to examine the loads on the spine during the gymnastic maneuver Back Walkover. Tests on a single female gymnast were made at the sports engineering lab at the University of Adelaide in Australia. Using the 3D-camera system; Optitrack Motion Capture System and Kistler Force Plate, positional data for two dimensions, X-direction (anterior-posterior) and Z-direction (vertical), and ground force were received. Data received were progressed into a graph, diagrams and biomechanical calculations where forces for the vertebrae L1 were calculated in vertical and horizontal direction. The received forces were compared to vertical and horizontal forces in L1 during standing position. Together with developed videos this assisted to model the loads of the spine (L1) during the gymnastic maneuver the “Back Walkover”. The study has led to a deeper knowledge for the community about the risks for female gymnasts and has widened the experience of the project participant, as the project aimed.
# Table of contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 Introduction</td>
<td>4</td>
</tr>
<tr>
<td>2.0 Addressing the problem Area</td>
<td>4</td>
</tr>
<tr>
<td>3.0 Aim and Objectives</td>
<td>5</td>
</tr>
<tr>
<td>4.0 Theoretical framework</td>
<td>6</td>
</tr>
<tr>
<td>4.1 The human body and anatomy of the spine</td>
<td>6</td>
</tr>
<tr>
<td>4.1.1 The lumbar region</td>
<td>7</td>
</tr>
<tr>
<td>4.1.2 Back extension</td>
<td>8</td>
</tr>
<tr>
<td>4.2 Common injuries in gymnastics</td>
<td>8</td>
</tr>
<tr>
<td>4.2.1 Injury in lower back</td>
<td>9</td>
</tr>
<tr>
<td>4.3 Disc herniation</td>
<td>10</td>
</tr>
<tr>
<td>4.4 Biomechanical methods to measure and analyze forces</td>
<td>11</td>
</tr>
<tr>
<td>4.4.1 Motion analysis and Optitrack Motion Capture System</td>
<td>11</td>
</tr>
<tr>
<td>4.4.2 Ground Force Plate</td>
<td>11</td>
</tr>
<tr>
<td>4.4.3 Electromyography</td>
<td>11</td>
</tr>
<tr>
<td>5.0 Methodology</td>
<td>12</td>
</tr>
<tr>
<td>5.1 Pilot study</td>
<td>12</td>
</tr>
<tr>
<td>5.2 Subject and Maneuver</td>
<td>13</td>
</tr>
<tr>
<td>5.3 Ethical consideration</td>
<td>14</td>
</tr>
<tr>
<td>5.4 Optitrack Motion Capture System</td>
<td>14</td>
</tr>
<tr>
<td>5.4.1 Markers</td>
<td>14</td>
</tr>
<tr>
<td>5.5 Kistler Force Plate</td>
<td>15</td>
</tr>
<tr>
<td>5.6 Inverse Dynamic</td>
<td>15</td>
</tr>
<tr>
<td>5.6.1 Data</td>
<td>15</td>
</tr>
<tr>
<td>5.6.2 Biomechanical calculations</td>
<td>16</td>
</tr>
<tr>
<td>5.7 Limitations</td>
<td>16</td>
</tr>
<tr>
<td>6.0 Result</td>
<td>16</td>
</tr>
<tr>
<td>6.1 Biomechanical Calculations</td>
<td>18</td>
</tr>
<tr>
<td>7.0 Discussion</td>
<td>19</td>
</tr>
<tr>
<td>7.1 Discussion Pilot study</td>
<td>19</td>
</tr>
<tr>
<td>7.2 Discussion methodology</td>
<td>20</td>
</tr>
<tr>
<td>7.3 Discussion of results</td>
<td>22</td>
</tr>
<tr>
<td>8.0 Conclusion</td>
<td>22</td>
</tr>
<tr>
<td>9.0 References</td>
<td>23</td>
</tr>
<tr>
<td>Appendix</td>
<td></td>
</tr>
<tr>
<td>Appendix A</td>
<td>- Consent Form</td>
</tr>
<tr>
<td>Appendix B</td>
<td>- The Placement of the Markers</td>
</tr>
<tr>
<td>Appendix C</td>
<td>- Frame 200, 215 &amp; 230</td>
</tr>
<tr>
<td>Appendix D</td>
<td>- Calculations</td>
</tr>
<tr>
<td>Appendix E</td>
<td>- Biomechanical calculations</td>
</tr>
<tr>
<td>Appendix E –</td>
<td>- Table; Percentages of total body mass (female)</td>
</tr>
<tr>
<td>Appendix F</td>
<td>- Data processing</td>
</tr>
</tbody>
</table>
1.0 Introduction
The sport of gymnastic is associated with a young starting age and an early specialization in certain skills. A starting age of only six years old would not be unusual for female gymnasts. In addition, considering that the typical career should be no longer than 10 years from this start date, the increase in the demands of the skill can cause significant health and medical issues. While the positive benefits of exercise such as gymnastic are obvious, one of the main concerns for the female aesthetic athlete is that of back pain. This is particularly relevant and related to the concerns of growth, skeletal maturity and overuse (Caine and Nassar, 2005). To examine if the repeated hyperextension and therefore also the repeated impact forces of the lumbar spine at female gymnasts may contribute to spinal problems is of importance (Hall, 1986). A common method used to examine maneuvers and analyze movement is the use of 3-dimensional cameras and ground force plate.

2.0 Addressing the problem area
It is well known that pain in the aesthetic athlete’s back in gymnastics is common and is often related to growth and overuse. Most female gymnasts will get some sort of injury during these years of training and competing and to better understand the biomechanical factors responsible for injury is important (D’Hemecourt and Luke, 2012; Caine and Nassar, 2005). The equipment in women’s artistic gymnastics is often changed to help reduce the loads on the body and reduce injuries that may occur. Examples of arrangements that have helped decrease the force on the gymnast during the landing from their maneuvers are square foam pits, shredded loose foam pits and resi-mats (Caine and Nassar, 2005). It is of interest to study mechanical loads on a female gymnast since they show higher occurrences of stress-related pathologies of the lumbar spine (Hall, 1986).

Injuries and problems common at the elite level of gymnasts are spondylosis (osteoarthritis of the joints between the center of the spinal vertebrae), vertebral apophyseal compression fractures and mechanical back pain. The pain can arise slowly in the beginning and is often noticed when the gymnast performs the maneuvers “back flip” or “back walkover” (Lyle and Micheli, 1987). The gymnastic maneuver Back Walkover and other different gymnastic maneuvers contribute to a variety of mechanical stresses placed on the spine. During the Back Walkover, vault and handspring, large lateral and vertical impact forces follow on the spine (Quinn, 2014). Earlier studies have shown negative changes in injuries on the disk and spine on elite level female gymnasts (Lee et al. 2006). According to NCAA (National Collegiate Athletic Association, a nonprofit organization that organizes the athletic programs of many universities and colleges in the USA and Canada) women’s gymnastics at collegiate level have the highest percentage of injury rate compared to the other observed sports. Female gymnasts seem to have more problems in the lower back than the rest of the female population (Hall, 1986). During a test where 100 female gymnasts in the age range of 6 to 24 went through a genographic analysis there was reported four times higher incidence of pars interarticularis defects compared to the 2.3% in the general female population. All of these stress-related pars defects were found in the lower lumbar region (Jackson, 1976).
3.0 Aim and objectives
The aim of this project is to investigate the loads on the lower back (L5-L1) of a female gymnast performing a typical maneuver called “The Back walkover” (Figure 1). The goal is to determine if that is an exercise that could contribute to lower back pain or put an athlete at risk.

Additionally, as the author of this project is a biomechanical engineer student, the second aim is to practice a 3-dimensional camera system and force plate. This knowledge and experience is valuable in further research in the area of biomechanics. Gymnastics has always been of interest to the author and after studying anatomy, the issue of how bad the gymnastic maneuver “Back Walkover” is for the lumbar spine was raised.

Figure 1: The sequence of a Back Walkover
4.0 Theoretical framework
Below is an account of the theory the project is based on.

4.1. The human body and anatomy of the spine
The vertebral column (spine) links upper and lower extremity. The vertebral column works as an elastic mainstay that supports and provides flexibility to the human body. Another key purpose of the vertebral column is to protect the spinal cord. The vertebral column consists of 33 vertebrae of which 24 vertebrae are moveable. Discs, muscles and ligaments attach to the vertebrae (Hamill and Knutzen, 2009). The structure of the vertebral column is complex and the spine is divided into different parts such as; cervical region (C1-C7), Thoracic region (T1-T12), Lumbar region (L1-L5), Sacrococcygeal region and Coccyx. See Figure 2.

![Vertebral Column](image)

**Figure 2: Vertebral Column (Rizuan, 2008)**

When the vertebral column is examined for loads it serves as a spring-like reaction, because of its curved shape. There are four curvatures in the spine. The cervical region forms a convex curvature to the anterior side of the body. The thoracic region forms a curve convex to the posterior side of the body, the lumbar region forms a curve convex to the anterior side of the body and the last curve is sited at sacrum and coccyx. These four curves provide more strength to the vertebral column and add balance to the human body. The connecting areas between every curvature at the column are the area where most mobility in the spine appear and so also a place of high injury condition. If the curvatures of the spine are more flattened the spine will be stiffer and more curvature of the spine will offer more mobility (Hamill and Knutzen, 2009).
Between each vertebra in the vertebrae column the movement is fairly small but to study the vertebrae column as a whole it is gifted with significant range of motion (Hamill and Knutzen, 2009). In the human spine the geometry is different at each spine level, for example the size and dimensions of the vertebrae, the curvature of the facet joint and the height of the vertebral discs. Even if people seem to have similar stature, there are variations in the vertebral spine; because of this the biomechanical effects could look slightly diverse in different bodies (Kuo et al. 2010).

**4.1.1 The lumbar region**

In the lumbar vertebral column there are 5 separate vertebrae, L1 to L5. The lumbar vertebra is larger compared to the others in the vertebral column. The lumbar vertebra consists in a vertebral body, a large block. The lumbar vertebrae bodies/ blocks are wider side to side than anterior to posterior. The curve consisted of the five lumbar vertebrae is weight bearing and furthermore influenced by the position of lower extremity and pelvis. The lumbar region and the cervical region are the most mobile areas of the vertebral column (Hamill and Knutzen, 2009; Bogduk, 2005).

The block is shaped as a tube and thicker on the front side where it also absorbs great quantities of compressive forces. Between each block (vertebra) there is an intervertebral disc that binds the vertebrae together and allows movement in the vertebral column. The discs between the lumbar vertebrae are big. The lumbar discs are thicker ventrally than dorsally which contributes to the anterior concavity. The discs distribute the loads in the vertebral column. The disc can stand compressive forces, bending and torsional. There is water in the discs that decrease during the day because of daily activities. This can cause the axial loading on posterior joints to increase. The water content in the discs refills at night and during rest (Hamill and Knutzen, 2009).

The lumbar vertebrae are taller among males than females. The angles at the lumbar vertebra are slightly different from the other region vertebrae at the vertebral column. The highest disc height is between L4-L5 and L5-S1; that is also where most mobility is possible compared to the rest of the lumbar joints (Hamill and Knutzen, 2009). The lumbar region develops support from ligaments, for example the important iliolumbar ligament. Also thoracolumbar fascia is an important support structure to the lumbar region in the spine. The fascia also assists the spine during flexion and extension. In the lumbar region the ranges of motion (ROM) are large both in extension and flexion (Hamill and Knutzen, 2009). The muscle iliopsoas is famous as a “dancer” muscle and links hip, pelvis and the lumbar spine together (Quinn, 2014).

According to Hamill and Knutzen (2009) flexion and extension for the total spine occur approximately 110 to 140 degrees; the movement is free in the lumbar and cervical regions and limited in flexion and extension at the thoracic region.
4.1.2 Back extension
The first step in back extension movement is that the pelvis tilt posterior. In the following steps of the back extension, activation in the lumbar leads and is primary during the movement. When the lower extremity is unilateral during back bending, related movements between pelvic and trunk are superior and more complex. When the weight is shifted back during back-bending (extension), pelvic moves forward (Hamill and Knutzen, 2009).

4.2 Lower back injuries and other common injuries in gymnastics
Lower back injuries often inhibit performance at the gymnasts training schedule (Lee et al. 2006). The lumbar back region in the vertebral column is the most injured mainly because of the loads the lumbar transmits. In activities such as gymnastics, figure skating and ballet, abnormal stress occurs on the apophyseal joints. Low-back pain can occur at several places in the lumbar. Muscles are often the problem while abrupt onset pains occur, irritated by a rapid movement for example. Low-grade chronic type of pain in the lower back is often seen as consequence from overuse (Hamill and Knutzen, 2009).

Earlier studies present that spine injuries and disc diseases are more common in female gymnasts that compete at a high level (Lee et al. 2006). Among advanced level female gymnasts nonspecific pain conditions and overuse are common (Caine and Nassar, 2005). In the maneuver Back Walkover impact forces and hyperextension occur in the lumbar parts of the spine (Hall, 1986). According to Garrick et al (1980) sprains that involve the back, and more specifically in the lumbar region, occur more often in gymnastics compared to other athletic activities. The work from Garrick et al. (1980) also identifies reasons for improvement in female gymnastic with preventive programs. Caine and Nassar (2005) have examined different studies and found that injuries in young (0-18 years old) male gymnasts are mostly in the upper and lower extremities followed by head injuries and on the spine and trunk. The difference in injuries between male and female gymnasts may depend on the different equipment girl and boy gymnasts are using. For example, male gymnasts put greater physical demands on the upper extremities. Lower back injuries are much more common in female gymnasts compared to male gymnasts. This will not only be because the female body and male body are different but also because the competitive gymnast sport is different for the different genders (Caine and Nassar, 2005). Female gymnasts put their spine in extreme range of motion frequently and several maneuvers they perform have high impact on the spine (Quinn, 2014). Lumbar region pains in female gymnasts are often first noticed with hyperextension activities such as Back Walkover (Hall, 1986).The disorder in the lower back of female gymnasts may appear from a single accident but more often as a consequence of repeated exercises, as in twisting during the gymnastic maneuver, hyper flexion and hyperextension in the back (Lyle and Micheli, 1987). Elements that can contribute to the mechanical stresses on the spine during the gymnastic maneuvers could be an imbalance in the core and pelvic area of the gymnast. Pain and injuries can result from the body’s lower extremity’s flexibility and strength, or example lack of strength in combination with ligaments close to the joint that are too flexible (Quinn, 2014). There appears to be a lot of exercises and maneuvers for the female gymnast where repeated hyperextension in the back occurs commonly (Lyle and Micheli, 1987). According to a study done by Hall (1986) the maneuver Back Walkover requires one of the greatest amounts of
lumbar hyperextension compared to other common gymnastics maneuvers. Either hands or feet maintain the impact force and it is very close in time to when lumbar hyperextension is at max.

Unlike ankle injuries that are more often sudden onset injuries, lower back injury occurrence is gradual (Caine and Nassar, 2005). Even if the pain in the lower back is first noticed in a gymnastic movement, later the pain can increase and be felt during everyday activities such as sitting in a classroom. Even taking a supine position such as lying on the back will increase the pain (Lyle and Micheli, 1987). At the aesthetic athlete lumbar lordosis contributes to several spine injuries. Poor technique in the gymnastic maneuver precedes risk of injury (Quinn, 2014). The loads on the back and certainly on the lower back are of significant interest as the shocks the spine and muscles around the spine have to absorb are generally large. Additionally, it takes a lot of strength and a vast range of motion to perform gymnastic maneuvers such as The Back Walkover (Lyle and Micheli, 1987). The movement involves a force transferring through the low extremity through the spine to upper extremity (Quinn, 2014). Identifying commonly injured sites would be of significant importance in order to advise sports personnel when extra attention and care could be needed (Caine and Nassar, 2005). The following table (Table 1) shows percent comparison of injury location in girls’ club and high school gymnastics (Female, 0-18 years old).

<table>
<thead>
<tr>
<th>Researcher</th>
<th># subjects</th>
<th>Club: Prospective studies</th>
<th>Club: Retrospective studies</th>
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<tr>
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<td>Weiker 1985</td>
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<td>Caine 2003</td>
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<td>Caine 1989</td>
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<tr>
<td>Lindner 1990</td>
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<td>Kolt 1999</td>
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<td>Steel 1983</td>
<td>146</td>
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<td>13.7</td>
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<tr>
<td>Kerr 1988</td>
<td>-</td>
<td></td>
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<td>Dixon 1993</td>
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<tr>
<td>Homer 1992</td>
<td>49</td>
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<td>24.4</td>
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Table 1: Percent comparison of injury location in girls’ club gymnastics (0-18 years old). Adapted from Caine & Nassar 2005.

According to studies examined by Caine and Nassar (2005) the most common injured body part of the spine and trunk is the lower back. Injuries reported on young (0-18 years old) gymnasts include both injuries from drastic/special event and gradual onset injuries. Therefore it is difficult to say if pain in lower back is because of a specific maneuver or a given event.

4.2.1 Injury in the lower back
The most vastly loaded structure in the skeleton is the lumbar vertebrae (Hamill and Knutzen, 2009). When examine an injury it is importance to consider several different variables causing the pain, also small, repetitive loads over time could be the main reason for pain. Pain is not necessary arise from a high load (Mc Gill, 1997).
Extension, flexion, asymmetrical loading and lateral flexion generate a bending force and they all cause both compression and tension in the disc between the vertebrae in the vertebral column (Hamill and Knutzen, 2009).

It is not clear what causes pain in the lower back and clearly several different factors can be involved. For example, factors such as repetitive work or maneuvers that twist or bend the back. Repetitive loading over a period of time can be the reason such as an uncoordinated or abnormal lift. High incidence of back injury comes from a sudden or unexpected load or from maximal efforts (Hamill and Knutzen, 2009). Pain and injury in the lower back occurs from excessive mechanical loads and the characteristics of the loads themselves such as torsion, shear, compression and bending (McGill, 1997). The extension muscles in the back are slow postural muscles and possibly will not generate force fast enough to avert extreme twisting or bending in the spine when sudden load applied. To prevent postural disturbance from an unexpected loading, the extensor muscles can increase the compressive force. This could lead to a combination of bending stresses and high compression on the vertebrae (Hamill and Knutzen, 2009). Injury in the lower back may occur from repeated and long loading on a specific tissue. An injury on the tissue or vertebrae occurs when loads applied on the tissue surpasses the tolerance of the tissue, which can lead to vertebral fracture or ligament avulsion (McGill, 1997).

Spondylosis and spondylolisthesis happen more often in the lumbar region compared to other regions in the spine (Hamill and Knutzen, 2009). The discs between vertebrae L4/L5 and L5/S1 are the spots most associated with problems. It is of interest to researchers to examine the biomechanical behavior on the lumbar spine and investigate how daily posture and dissimilar loads from altered angles can affect the forces applied onto the lumbar spine (Kuo et al. 2010).

The strength and flexibility of the muscles around the spine also have an impact on low-back pain. Lack of flexibility in the iliotibial band and hamstrings that are too tight are two examples of conditions that are associated with low-back pain (Plowman, 1992). Enlarged stress on the posterior elements on the spine (including the pars interarticularis, pedicles and facet joints) and anterior tilt of the pelvis can occur from weak lower abdominals, tight iliopsoas, weak gluteal and tight thoracolumbar fascia (Quinn 2014). Another muscle factor that can affect low-back pain is weak abdominals because they control the pelvis. Lack of control and strength of the pelvis can result in hyper lordosis (swayback). A hyper lordosis position puts excessive stress on the intervertebral disc and on the posterior apophyseal joints. The muscles Erector spinae are also possible muscles involved in low-back pain. To predict low-back pain, fitness, strength and flexibility can be important even if it may not prevent a person from low-back pain (Plowman, 1992). Strengthening abdominal muscles, hamstring flexibility and hip flexor can contribute to less pain in the lumbar region and execution of proper technique during the tasks (Quinn, 2014).

4.3 Disc herniation
In the vertebral column the intervertebral discs in the lumbar region have the highest rate of disc prolapse compared to any other segment (Hamill and Knutzen, 2009). According to Adams and Hutton (1982) disc herniation from one-time application of load is not common at all. When the spine is neutral and is exposed to compression it
is extremely rare that disc herniation occurs. Compression in high-velocity often results in terrible vertebral burst fractures (McGill, 1997).

4.4 Biomechanical methods to measure and analyze forces
To better analyze reasons and injury patterns it is of importance to recognize the intricacies of the biomechanics. Using biomechanical modeling techniques can help assess the risk of injury and improve training and rehabilitation programs (McGill, 1997).

4.4.1 Motion analysis and Optitrack Motion Capture System
To receive kinematic data, Optitrack Motion Capture System is an established apparatus to capture and analyze movements. The Optitrack Motion Capture System records actual movements and translates the movement into digital data. It is not solely used in Biomechanical measuring and research – it is also commonly used to animated movies and in the videogame industry. Other areas where the Optitrack Motion Capture System is used, for example, the performing arts, sports and the medical field (Wu and Boulanger, 2011). The Optitrack Motion Capture System uses infrared illuminators and the markers placed on test subject are retro-reflective to reflect the infrared light back to the cameras. Other similar system uses LED markers instead. The equipment is precise but still can include outliers, noise and missing of data for a time period. A big reason for missing markers is that the markers have been blocked for example, by things on set or body parts, or that the markers have not been seen by enough cameras. Outliers can occur when the markers’ positions are very close and as a result the system confuses the markers with the nearby marker and miss-tracks the marker’s location. To correct these miss-tracked data from the recording it necessitates correction by manual editing which demands a major amount of time and can contribute to human mistake correcting the data by hand. Optitrack Motion Capture System is, among other motion capture techniques, the most generally used (Dyson, 2011; Wu and Boulanger, 2011). To create a movement pattern that looks realistic for modeling the human body's movement it demands a great number of degrees of freedom and useful control methods. To simplify the model makes it easier but also risks unrealistic movements. A complex model can hopefully result in motions that appear more natural. Today’s animation tries to force the complexity into algorithms rather than skilled manual manipulation (Monheit and Badlery, 1990).

4.4.2 Ground force plate
To monitor vertical and lateral ground reaction forces, a force platform can be used. Hall (1986) used a force platform to monitor vertical and lateral ground reaction forces for amongst others the maneuver Back Walkover. A ground force plate is commonly used during studies and test where the athletes’ movement is included, for example in sports and maneuvers including jumps, sprints, explosive movements etc. (Decker et al. 2003, Chappell et al. 2002, Cavanagh and LaFortune, 1980).

4.4.3 Electromyography
Electromyography (EMG) is a method used for motion analysis. During athletic activities EMG recordings are used to determine activities in the muscles. When muscles contract the EMG signal can measure the electrical currents created from the muscle contraction. The EMG-signal is reliant on the physiological and anatomical properties of the muscles and controlled by the nervous system.
In biomedical engineering the use of EMG signals is becoming an important tool and there is an interest for biomedical applications and research. One important submission area is the field of management and rehabilitation of motor disability and EMG could be of importance for example in rehabilitation reason, to discover and therefore prevent injury patterns and what a performance could require. (Moynes et al. 1986; Reaz et al. 2006)

5.0 Methodology
The project aimed to model and evaluates the force reactions and moments in the spine (L1-L5) during the gymnastic maneuver Back Walkover. All tests took place in the sports engineering lab at the University of Adelaide.

5.1 Pilot study
Pilot tests were done together with Ph.D. student Kimberly Andersen (sports engineering) to learn the sports lab and the equipment. The first test was done with 14 markers. At the first pilot test no markers on upper body or upper extremity were attached. The amount of cameras catching the movement was comprised of 12 cameras. The gymnastic maneuver was divided into two trials, Trial A and Trial B. In Trial A the last foot leaving the ground in the maneuver is on the force plate until leaving it. In Trial B both hands are put down during the maneuver and later on removed. The test subject was involved during the pilot tests. Markers were positioned on the subject’s body. See Figure 4 for the markers placement for Pilot test 1.

<table>
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</tr>
<tr>
<td>RTOE</td>
<td>Dexter 5th Metatarsal head</td>
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<tr>
<td>LANKLE</td>
<td>Sinister Lateral Malleolus</td>
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<td>RANKLE</td>
<td>Dexter Lateral Malleolus</td>
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<td>LKNEE</td>
<td>Sinister Lateral Epicondyle femur</td>
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<tr>
<td>RKNEE</td>
<td>Dexter Lateral Epicondyle femur</td>
</tr>
<tr>
<td>LGRTROC</td>
<td>Sinister Greater trochanter femur</td>
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<td>RGRRTROC</td>
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<td>L4</td>
<td>Vertebra Lumbal 4</td>
</tr>
</tbody>
</table>

<table>
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<th>Placement</th>
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<tr>
<td>LTOE</td>
<td>Sinister 5th Metatarsal head</td>
</tr>
<tr>
<td>RTOE</td>
<td>Dexter 5th Metatarsal head</td>
</tr>
<tr>
<td>LANKLE</td>
<td>Sinister Lateral Malleolus</td>
</tr>
<tr>
<td>RANKLE</td>
<td>Dexter Lateral Malleolus</td>
</tr>
<tr>
<td>LKNEE</td>
<td>Sinister Lateral Epicondyle femur</td>
</tr>
<tr>
<td>RKNEE</td>
<td>Dexter Lateral Epicondyle femur</td>
</tr>
<tr>
<td>LGRTROC</td>
<td>Sinister Greater trochanter femur</td>
</tr>
<tr>
<td>RGRRTROC</td>
<td>Dexter Greater trochanter femur</td>
</tr>
<tr>
<td>LPSIP</td>
<td>Sinister Posterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>RPSIP</td>
<td>Dexter Posterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>LASIS</td>
<td>Sinister Anterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>RASIS</td>
<td>Dexter Anterior Superior Iliopsoas Spine</td>
</tr>
<tr>
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</tr>
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<td>L1</td>
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</tr>
<tr>
<td>T4</td>
<td>Vertebra Thorcal 4</td>
</tr>
<tr>
<td>C7</td>
<td>Vertebra Cervical 7</td>
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<td>LSHOULDER</td>
<td>Sinister Acromion process</td>
</tr>
<tr>
<td>RSHOULDER</td>
<td>Dexter Acromion process</td>
</tr>
<tr>
<td>LELBOW</td>
<td>Sinister Medial Epicondyle</td>
</tr>
<tr>
<td>RELBOW</td>
<td>Dexter Medial Epicondyle</td>
</tr>
<tr>
<td>LWRISt</td>
<td>Sinister Head of Ulna</td>
</tr>
<tr>
<td>RWRIST</td>
<td>Dexter Head of Ulna</td>
</tr>
<tr>
<td>CHEST</td>
<td>Mastaborium of Sternum</td>
</tr>
</tbody>
</table>

Figure 4:
Markers Placement Pilot test 1

Figure 5:
Markers Placement Pilot test 2
So as seen in Figure 4 the markers on the back were put on L4 and L5. Later on, processing the data in AMASS, the markers L5 and L4 were too close to be separated as two different markers based on the close distance they had. Therefore the decision to change one marker from L4 to L1 was made. This was a very important incident for the project to discover and changed the direction of the project early in the project's process.

In the second pilot test the project participant, after discussing with colleagues, decided to add more markers to the test subject’s body. The upper extremity, see Figure 5, was marked up to add a superior visualization of the maneuver in the data program. The markers on the upper extremity only purpose were for visualizations and used for calculations. During the second Pilot test the cameras were placed the same way because of good results from the first Pilot test. A problem occurring during the second pilot test was that the cameras were too low to catch the markers on the hands and arm during the beginning and the end of the maneuver. In order to facilitate the following of the movement of the spine there was a decision to put a marker on vertebræ T4, C7 and on the chest. After the second pilot test data from the markers was put into AMASS to process. For the real tests more cameras were added and the angles and the height of some of the cameras were changed. Furthermore markers were added on each side (on the muscle M. erector spinæ) of the L1-marker. Two markers were also attached at temporal surface on each side of the head and one extra marker on the chest; these were also for visual effects only.

5.2 Subject and Maneuver

The project aims to examine the loads on the lower back during the gymnastic maneuver Back Walkover, for this only one single test subject is required. The decision on choosing one test subject is based on the time limit this project has and the aim of the project that will still be fulfilled with one test subject. The maneuver Back Walkover could look very different from each gymnast performing it; so examining many different gymnasts could result in different looking maneuvers with different result in forces to the lumbar. This could be of interest to examine for further studies or to develop the project. One of the motives for this project is to learn the equipment using 3-dimensional cameras and force plate. Merely examining the loads at one single gymnast is necessary for that motivation.

The test subject was a female gymnast of 24 years old. The subject’s weight was 588 N and height was 1, 63 m. She had a background of gymnastic and performs the maneuver Back Walkover on a recurrent basis. In order to attach the markers and for the maneuver to be clearly visible the test subject had to wear skins and a sports bra during the tests. The maneuver begins in a standing position and then the person bends backwards until the hands reach the ground. In the moment the hands reach the ground the last foot leaves the ground and goes over the head like a bow. See Fig 1. During the maneuver Back Walkover, hyperextension in the back is produced (Quinn 2014). The maneuver Back Walkover is produced at the floor or on the gymnastic balance beam. So to say, there is not any specific equipment used that has huge impact on the body during this maneuver.
5.3 Ethical consideration
In order to conduct research involving human subjects there are always ethical issues that need to be considered. The chances for injuries during this test are considered to be low risk. The test subject’s task for this project is measured as low risk since the test subject did not do any maneuver or movement she was not used doing on a regular basis in daily life. The maneuver “Back Walkover” is commonly performed and the test subject is perfectly healthy. To be exempt from ethical review at the University of Adelaide (where the tests took place) the research had to satisfy the conditions:

“It is ‘negligible risk’ research: there is no foreseeable risk of harm or discomfort; and any foreseeable risk is no more than inconvenience”… (The University of Adelaide, Levels of Ethical Review. 2014-02-27)

Therefore a consent form was given to the test person to sign explaining the circumstances and to make sure the test person understood and accepted the conditions. See Appendix A.

5.4. Optitrack Motion Capture System
The project used 3-dimensional Optitrack Motion Capture System cameras located in the sports engineering laboratory at the University of Adelaide. The system shows data from every marker placed on the test subject’s body in three dimensions, X, Y and Z.

With the help of the Optitrack Motion Capture System the kinematics of the movement were measured. The system uses retro-reflective markers which are attached to the test subject’s body. Placing the markers on the body allows joints, segment and movement patterns to be portrayed. The retro-reflective markers are designed to reflect IR (infrared) light radiated from the diodes placed around the camera lens. The cameras can determine the exact position of the markers in 2-dimensional space with an accuracy of sub-millimeter (Dyson, 2011)

With the help of Optitrack Motion Capture System, each markers position was recorded and from the data experimental kinematics was calculated. For this project 14 cameras were used to track the position of all markers. The maneuver demanded many cameras because the movement is so complex and many markers will be on the underside of the body during the main part of the maneuver, from standing to standing again. Additionally each marker must been seen by a minimum of three cameras.

5.4.1 Markers
There were a total of 27 markers placed on the test subject’s body, see Figure 4. For placement of the markers see Appendix B.

The test subject wore skins and a sports bra to simplify palpation for placement of the markers on the test subject’s body and to avoid alteration of the markers during the maneuver. There were markers placed on both legs, even though it was only the standing leg’s information that was of interest. Upper extremity and upper trunk were also marked with markers with purpose to give a better visual effect. Except the arms and wrists, also chest, trunk, neck and head had markers for visual effect only. During the pilot tests the marker for L1 was hidden during the maneuver by the Musculus Erector spinae, therefore two extra markers was added on both sides of L1. Four markers were also placed on each corner of the Kistler Force Plate for the force plate to be easy to spot during data progressing in AMASS.
5.5 Kistler Force Plate
To measure the ground reaction forces the project used the Kistler Force Platform to express how the force from the ground changes during the maneuver “Back Walkover”. The ground reaction forces of the maneuver were measured in two different parts. The first part measured the ground reaction from when the last foot leaves the ground and the second part measured hands touching the ground until hands leaving the ground again. There were several trials for both foot and hands touching the force plate, for each trial ground reaction forces were collected to receive the external kinetics.

5.6 Inverse dynamic
Inverse dynamics is a technique used to calculate loads, torques and moments of force from kinematics. It is based on kinematics which describes the movement of the body and the body's inertial properties - mass and moment of inertia. From the kinematic data there were velocity, acceleration, position and displacement. For this reason understanding of the musculoskeletal joint system are required.

The ground reaction force (kinetics) arrives from the ground to the part of the body touching the ground. In this specific case it was for the first part (from the last foot leaving the ground), second part (from both hands touching the ground). To collect all the data necessary the project used Optitrack Motion Capture System and Kistler Force Plate. The kinematic data were calculated from the markers positions recorded by Optitrack Motion System and the kinetic data collected thru Kistlers Force Plate.

5.6.1 Data
Data received from Optitrack Motion System and from Kistler Force Plats were analyzed and processed in the data program Microsoft Excel. Videos and pictures were also developed with help of the software Matlab. Data were processed to explore angles, acceleration and as values for the biomechanical calculations. To receive a better visualization and understanding how the forces are changing during the maneuver, plots and diagrams were created in Microsoft Excel.
5.6.2 Biomechanical Calculations

Biomechanical calculations were done mostly through Microsoft Excel and also sketched by hand for a better visualization and understanding. For the biomechanical calculations one trial (with last foot leaving ground) and that Trials’ data were used. This trial was chosen based on the quality of the data. The project wanted a trial with last foot leaving ground to facilitate the biomechanical calculations. To calculate the forces on the vertebrae L1 in lumbar spine the ground force on the foot for vertical and horizontal direction had to be used. The standing leg of test person’s body was divided into different segments to avail for the biomechanical calculations; segment A (foot-ankle), segment B (ankle-knee), segment C (knee-hip) and segment D (hip-L1) for the biomechanical calculations. In “segment A” the forces in Z- and X-direction in the ankle was asked for. The forces received from calculations at segment A were brought to the calculations for segment B, were the force in Z- and X-direction for the knee was asked for. The procedure proceeded like this for all segments to the final in segment D. There was no momentum in the calculations as the toe is reckoned as a fixed part to the ground.

The mass of each segment was calculated through a method from Plagenhoef et al. (1983) where the mass of each segment is measured from the body weight. See Appendix E and Appendix K. The center of mass of each segment was calculated from the markers position and trigonometry. See Appendix K.

5.7 Limitations

This project aimed to model in 2-dimension instead of 3-dimension. The project was still to use the Optitrack Motion Capture System 3D camera. The decision to model in 2D instead of 3D was on the basis of the time limit this project had. Also the project aims to investigate only two forces, one in vertical direction and one in horizontal direction, therefore 2-dimensional is enough.

There was one Kistler Force Plate available at the sports engineering lab at the University of Adelaide. Therefore the project had to do two different trials. The first Trial had to be when last foot was leaving the ground and the second Trial had to be where both hands were placed on the ground until they left the ground. The reason for this was to develop a better overview and understanding of the whole movement and the loads it brings to the body which were shown by the pilot tests.

6.0 Results

This project aimed to investigate the loads in the lumbar spine (L1-L5) and resulted in a graph describing the flexion in the hip during the maneuver and forces of vertebra L1 were received in the chosen directions. Another intention of the project was for the project participant to gain experience with biomechanical tasks like this.

Data were first handled and entered into the software AMASS where each marker was recognized to right body part (see Appendix B) for each frame. To recognize every marker took a great amount of time because of the accuracy needed. It was essential that it would be done correctly; otherwise data will get lost or assorted with other markers as one example. Video of the maneuver and force diagram was exposed using Matlab.

Through Optitrack Motion Capture System data were recorded from each markers position and data from Z (vertical) - and X (anterior-posterior)-direction were
managed and disposed in Excel. Kistler Force Plate provided ground force reactions in three directions. For the biomechanical calculations two directions were used, Z-direction (vertical) and X-direction (anterior-posterior). To find the place during the Back Walkover maneuver where most hyperextension in lower back befalls, the angle for the hip flexion (see Figure 7 for example) was calculated in several steps using Excel.

**Figure 7: Angle for the hip flexion**

The angle was calculated for every frame during the maneuver (see Figure 7 for measured angle, see Appendix J for calculations). An intended coordinate system was pictured with the hip marker as origin to facilitate the calculations to receive the desired angle. The received angles were plotted in Excel into a graph that shows the flexion in the hip, see graph below (Figure 8). The graph shows how the movement starts standing, and then simultaneously as the back is bending, the angle at the hip increases -therefore the curve in graph rises (Frame150-230). The graph sinks after the legs have gone over the head (handstand position) because of the position of body that is now like a person bending forward (around Frame 334), the angle at the hip is now very low. It ends with standing position again (Frame 410). The graph shows that the flexion angle at the hip are prime around frame 200-230 and therefore the most hyperextension in the back follows there as well. The peak is at frame 215, there the angle at the hip anterior side are 232, 8°. Appendix C shows the leg and the markers position for frame 200, 215 and 230. The project participant discussed with experts and then chose to do the biomechanical calculations with the frame 200, 215 and 230, with 15 frames in between. The reason for this distance between the chosen frames is necessary to acquire some visible changes throughout the biomechanical calculations.
Figure 8: The curve shows the change for flexion angle in the hip for each frame.

6.1. Biomechanical calculations
Frame 215 is where most hyperextension in the lower back occurs. Therefore the biomechanical calculations where done by position data from frame 200, frame 215 and frame 230. Between each frame chosen, (200 to 215 and 215 to 230) 0.15 seconds pass. The results received throughout the calculations (See Appendix E) (explained in 5.6.2 Biomechanical calculations), were:

<table>
<thead>
<tr>
<th>Forces [Newton]</th>
<th>X-direction</th>
<th>Z-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe</td>
<td>181.933 [N]</td>
<td>634.074 [N]</td>
</tr>
<tr>
<td>Ankle</td>
<td>181.970 [N]</td>
<td>641.893 [N]</td>
</tr>
<tr>
<td>Knee</td>
<td>186.077 [N]</td>
<td>674.378 [N]</td>
</tr>
<tr>
<td>Hip</td>
<td>200.740 [N]</td>
<td>745.995 [N]</td>
</tr>
<tr>
<td>L1</td>
<td>208.222 [N]</td>
<td>847.222 [N]</td>
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</table>

Table 2: Forces L1; Frame 215 - Critical Point during the Back Walkover

<table>
<thead>
<tr>
<th>Forces [Newton]</th>
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<th>Z-direction</th>
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</thead>
<tbody>
<tr>
<td>Toe</td>
<td>3.349 [N]</td>
<td>587.628 [N]</td>
</tr>
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<td>Ankle</td>
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<td>595.437 [N]</td>
</tr>
<tr>
<td>Knee</td>
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<td>626.858 [N]</td>
</tr>
<tr>
<td>Hip</td>
<td>3.349 [N]</td>
<td>695.882 [N]</td>
</tr>
<tr>
<td>L1</td>
<td>3.349 [N]</td>
<td>789.626 [N]</td>
</tr>
</tbody>
</table>

Table 3: Forces at L1 during standing pose

Conclusions can be made from the tables’ comparison. The loads on the spine (L1) differ from standing and the extreme point during the gymnastic maneuver ”Back Walkover”. In Z-direction the load on L1 is 847.222 N compared to the standing position where it is 789.626 N. Nevertheless the difference between the ground force in vertical direction on “toe” to the vertical force at L1 is almost the same value (~200 N) for both the critical point (Frame 215) and standing position, Frame 215: 213.148 N (847.222 N (L1) minus 634.074 N (toe)), standing position: 201.998 N (798.626 N(L1) minus 587.628 N(toe)).
In Z-direction the force on L1 during the “Back walkover” compared to standing has increased by 7.3% \((\frac{847.222 - 789.626}{789.626} \text{ N})\). In X-direction on the other hand, the loads have increased more significantly; from 3.349 N in the standing position compared to 208.222 N in horizontal direction (L1) during the critical point in the maneuver “Back Walkover”. (The values and data for the standing position were received from the same test trial as the “Back Walkover”).

The biomechanical calculations were done at L1 because it contained better data than L5. Acceleration was received through the markers data, in which manner their positions had changed in X-directions and Z-direction over time. See Appendix D. To view Biomechanical calculations, see Appendix E.

The lumbar spine offers a wide range of motion and is active during daily life, therefore also a place for high risk of injury. A study made by Kuo et al. (2010) showed that asymmetric forces exist in several postures and outcomes more intense with larger loading. According to Kuo et al. (2010) the magnitudes of the forces are larger in flexion compared to extension and axial rotation. This project, however, concerns hyperextension and not “normal extension”.

7.0 Discussion
The aims with this project were to model the loads on the spine (L5-L1) and for the project participant to obtain experience in practice of biomechanical methods. Modeling’s of the loads on the spine was done with the help of Microsoft Excel software, hand calculations and through videos. The critical point where most hyperextension occur in lower back, vertebrae L1, was found and forces in horizontal respective vertical direction were developed. The purposes were accomplished even though the modeling could have been of different appearance. Noticeably the project would have demanded more time in order for the modeling to be developed. Were the project member to do this again, a few variations would be made. The project aimed from the early start to examine and model the loads on the spine at the disc between L5/L4, this had to be changed because of the data acquired from Optitrack Motion Capture System. The marker on L5 was not visible for enough cameras during a certain time at the maneuver; therefore data were lost during important frames. As an outcome from this the project participant made the decision to use data from the marker at vertebra L1 instead, after discussion with super advisor and Doctor’s at the University of Adelaide.

7.1 Discussion of Pilot study
The Pilot tests were done early in the procedure and were of massive importance for the whole projects development. It is of significance for the project participant to learn how to use the equipment and software programs, how to rig cameras for best advantages, with beneficial angles and range of capture to catch every marker on the test subjects body during the maneuver. The maneuver itself was very complex so extra cameras were necessary to add and to try out the different positions of the cameras in order to find the best angles. As a result from the pilot tests more markers were added to the test subjects upper body and upper extremity during the process.

To sum up the pilot tests were of huge importance and had a great impact on the project. For the project participant to learn how to use the equipment and learn how to
solve problems that could occur, (one example of problem often occurring: cameras not discovered and recognized by the computer), was valuable for the real test trials. The pilot test brought many benefits and knowledge for the remainder of the project.

7.2 Discussion of methodology
The methods used in this project were of importance because it was also included into the aim of this project for the project participant to practice and get experience in biomechanical methods of motion analysis. In the opening of the project much time was given to learn the equipment and methods.

The biomechanical calculations could have been improved if the project participant was familiar with, for example, the software Matlab. Use of Matlab would have facilitated the modeling of the maneuver “Back Walkover”. It would have contributed with ease, preciseness, comprehensiveness and speed. The biomechanical calculations had to be calculated by hand. If the calculations would have been made with a data software program it would have saved the project a huge amount of time and effort.

Kistler force plate and Optitrack Motion Capture System were reasonably easy to use. There were often problems with the connection and the computer. Many times cameras went missing and the sync between the force plate and the camera system did not work. This took extra time but also added experience for handling the program better when disorder.

To add markers on the upper extremity and back was valuable for the visual effect and contributed to more easily understand the body and maneuver during data processing in the program. One negative factor occurring during the second pilot test was that a lot of important data went missing during very important parts of the maneuver. The reason for this is that every marker has to be seen by three cameras and the maneuver itself is very complex. The markers on the back were visible while the test subject was in standing position during the maneuver. During, for example, position 4 and 5 (see figure 1) (when the abdominal shows upwards), some markers could get lost for a few frames. The maneuver is also long and several markers point downwards the ground during the maneuver. For example, it was especially hard to catch the marker on L1. That marker was hidden by the close nearby back muscles erector spinae on each side of the spine.

The modeling was done on one single female gymnast. There was not a group of gymnasts compared. The reason for choosing one single test subject for this project is the time limit this project has and the significant quantity of data that needed to be processed. Furthermore, the issue proposed by this project is modeling the loads on the lower back in a “Back Walkover”; therefore exploit one single test subject fulfilled the purpose of the project. The maneuver “Back Walkover” will be slightly different for each person performing it; to specifically look at one person shows what this exercise could to with the loads on the spine on one individual person.

7.3 Discussion of results
With the funds that were available the project is content with the results. The differences between the forces in L1 vertical and horizontal during the “Back walkover” compared to the vertical and horizontal forces standing were not as high as presumed. When this project was still in idea phase the forces at the lumbar spine
were assumed to almost certainly be higher than the tests and calculations showed. The “normal load” in vertebrae L1 was hard to find background studies for. Hence the project did the same biomechanical calculations for L1 in a standing position for the same test subject. The differences were not as high as expected. The forces in vertebrae L1 were 7.3 % higher in Z-direction from standing to the critical point in the maneuver. In X-direction the difference and increase from standing to critical point was significantly higher. This indicates that a hyperextension in the back such as this is not normal compared with the forces in vertebrae L1 during standing position and that the increase of impact is much higher in X-direction (horizontal) than in Z-direction. To find similar projects that included actual numbers on devastating forces on the lumbar vertebrae were difficult. It is noteworthy that this project brings attention to this problem area that exists, especially for young (0-25 years old) female gymnasts and other aesthetical athletes. As read in Quinn (2014) and Lyle and Michelis (1987) study, other gymnastic maneuvers that have a high impact on the lower back spine are Back Handspring and Front Walkover, and sudden pain in the gymnasts’ lower back could occur during these implemented maneuvers. It is difficult to conclude which maneuver is most damaging to the spine.

The result could have been improved further. For example, the necessary alteration from vertebrae L5 to vertebrae L1 also adds more weight to the segment D (hip). This was harder to find a calculation for and instead the project had to accept it to be the same weight as for the hip. The decision to model on vertebrae L1 also had its advantages. Because of the distance from the hip to L1, the holistic image of the maneuver was clearer.

To produce the graph was a vital step in the project. On the graph the critical point (the peak) during the maneuver “Back Walkover” for this test subject could be found. The project required the modeling of the loads on the lumbar spine during the “Back Walkover”, so finding the place where most hyperextension in the lower back occurred was necessary for this project and compulsory for the start of processing the data (both project participant and super advisor were pleased with the received graph).

Video and documentation by camera were done from the project’s start, with the pilot test and the real test taking place later. This was valuable for the project writing, evaluations, and material and for the project presentations.

Injuries in young (0-25 years old) female gymnasts are common today, therefore it is of interest and importance to pay attention and focus on why they occur and what maneuver can cause this. This project chooses to focus on the maneuver “Back Walkover”, a motion that includes huge hyperextension in the lower back. This maneuver is common in female gymnastics but this type of hyperextension is not common in everyday life. The impact this maneuver has on the lumbar spine because of the hyperextension is not well known, therefore this project would be valuable for the community and especially for aesthetic athletes.
8.0 Conclusion
The project resulted in a vertical force and horizontal force in the vertebra L1 during the gymnastic maneuver "Back Walkover", compared to standing position the forces at L1 during the maneuver were increased by 14 percent. It is still hard to evaluate how dangerous these forces may be for the lumbar spine and there is not much research to compare with. It is also hard to say if the maneuver itself is the reason for injuries in the lower back in young female gymnasts; it could look very different from person to person. The conclusion still remains that repeated loading of this type contributes to an increased risk of injury in the lower back. The maneuver includes a hyperextension with a great angle from standing leg to lower back with the hip as origin that is not common in a daily life. This project also contributed to experience in motion analysis and different biomechanical methods for the project participant, which also was an aim for the project.

In conclusion, today in the community, it is of importance to consider different behavior and patterns that could lead to injuries. Especially in young girls, pain in the lower back is common and should be more deliberated. The sport of gymnastics has a high rate of injuries; therefore it is of importance to look deeper at each maneuver and which consequences could come out of it if not careful. Therefore, this project contributes to societal benefits and is a step forward in the aesthetical female athletes’ sports and interests.

The project participant appreciated the opportunity to be at the sports engineering lab at the University of Adelaide. It is also a valuable benefit to learn how to use Optitrack Motion Capture System and Kistler Force Plate, and the project participant hopes to bring this into future jobs.
9.0 References


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Lyle, J & Micheli, MD 1987 ‘Back injuries in gymnastics’, Division of Sports Medicine Children’s Hospital Medical Centr, vol. 2, no. 3.


Wu, Q & Boulanger, P 2011, ‘Real-time Estimation of Missing Markers for Reconstruction of Human Motion’ University of Alberta

Appendix A

Consent form
Human Research Ethics Committee (HREC)

CONSENT FORM

1. I have read the attached Information Sheet and agree to take part in the following research project:

<table>
<thead>
<tr>
<th>Title:</th>
<th>Researcher to insert title of the project as written on the participant information sheet.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethics Approval Number:</td>
<td>Researcher to insert this number (allocated once the project has been approved).</td>
</tr>
</tbody>
</table>

2. I have had the project, so far as it affects me, fully explained to my satisfaction by the research worker. My consent is given freely.

3. I have been given the opportunity to have a member of my family or a friend present while the project was explained to me.

4. Although I understand the purpose of the research project it has also been explained that involvement may not be of any benefit to me.

5. I have been informed that, while information gained during the study may be published, I will not be identified and my personal results will not be divulged.

6. I understand that I am free to withdraw from the project at any time.

7. I agree to the interview being audio/video recorded.  Yes [ ]  No [ ]

8. I am aware that I should keep a copy of this Consent Form, when completed, and the attached Information Sheet.

Participant to complete:

Name: __________________________ Signature: __________________________ Date: ___________

Researcher/Witness to complete:

I have described the nature of the research to __________________________

(print name of participant)

and in my opinion she/he understood the explanation.

Signature: __________________________ Position: __________________________ Date: ___________
## The Placement of the Markers

<table>
<thead>
<tr>
<th>Markers</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTOE</td>
<td>Sinister 5th Metatarsal head</td>
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<tr>
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<td>Sinister Greater trochanter femur</td>
</tr>
<tr>
<td>RGRRTROC</td>
<td>Dexter Greater trochanter femur</td>
</tr>
<tr>
<td>LPSIP</td>
<td>Sinister Posterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>RPSIP</td>
<td>Dexter Posterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>LASIS</td>
<td>Sinister Anterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>RASIS</td>
<td>Dexter Anterior Superior Iliopsoas Spine</td>
</tr>
<tr>
<td>L5</td>
<td>Vertebra Lumbal 5</td>
</tr>
<tr>
<td>L1</td>
<td>Vertebra Lumbal 1</td>
</tr>
<tr>
<td>T4</td>
<td>Vertebra Thoracal 4</td>
</tr>
<tr>
<td>C7</td>
<td>Vertebra Cervical 7</td>
</tr>
<tr>
<td>LSHOULDER</td>
<td>Sinister Acromion process</td>
</tr>
<tr>
<td>RSHOULDER</td>
<td>Dexter Acromion process</td>
</tr>
<tr>
<td>LELBOW</td>
<td>Sinister Medial Epicondyle</td>
</tr>
<tr>
<td>RELBOW</td>
<td>Dexter Medial Epicondyle</td>
</tr>
<tr>
<td>LWRIST</td>
<td>Sinister Head of Ulna</td>
</tr>
<tr>
<td>RWRIST</td>
<td>Dexter Head of Ulna</td>
</tr>
<tr>
<td>LHEAD</td>
<td>Sinister Temporal Surface</td>
</tr>
<tr>
<td>RHEAD</td>
<td>Dexter Temporal Surface</td>
</tr>
<tr>
<td>CHEST</td>
<td>Manubrium of Sternum</td>
</tr>
<tr>
<td>LL1</td>
<td>Sinister Erector Spinae, next to L1</td>
</tr>
<tr>
<td>RL1</td>
<td>Dexter Erector Spinae, next to L1</td>
</tr>
</tbody>
</table>
Appendix C

**Frame 200, 215 & 230**
The position for each marker, both in x-direction and z-direction, on the standing foot (left) during the time period (Frame 200-230) where most hyperextension in lumbar occurs.
Appendix D

**Calculations:** receiving acceleration

<table>
<thead>
<tr>
<th>Example, Frame 215</th>
<th>(d_1) ((z_2-z_1))</th>
<th>(d_2) ((x_2-x_1))</th>
<th>Length of segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Toe-ankle)</td>
<td>43.32</td>
<td>74.72</td>
<td>86.370</td>
</tr>
<tr>
<td>b (ankle-knee)</td>
<td>322.89</td>
<td>163.65</td>
<td>361.993</td>
</tr>
<tr>
<td>c (knee-Hip)</td>
<td>351.54</td>
<td>172.4</td>
<td>391.538</td>
</tr>
<tr>
<td>d (Hip-L1)</td>
<td>34.39</td>
<td>175.52</td>
<td>178.857</td>
</tr>
</tbody>
</table>

**Mass centrum distance**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>x-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Toe-ankle)</td>
<td>21.66</td>
</tr>
<tr>
<td>b (ankle-knee)</td>
<td>161.445</td>
</tr>
<tr>
<td>c (knee-Hip)</td>
<td>175.77</td>
</tr>
<tr>
<td>d (Hip-L1)</td>
<td>17.195</td>
</tr>
</tbody>
</table>

**Position mass centrum Frame 215**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>x-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Toe-ankle)</td>
<td>0.880</td>
</tr>
<tr>
<td>b (ankle-knee)</td>
<td>183.985</td>
</tr>
<tr>
<td>c (knee-Hip)</td>
<td>521.200</td>
</tr>
<tr>
<td>d (Hip-L1)</td>
<td>714.165</td>
</tr>
</tbody>
</table>

**Position mass centrum Frame 230**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>x-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Toe-ankle)</td>
<td>1.660</td>
</tr>
<tr>
<td>b (ankle-knee)</td>
<td>194.290</td>
</tr>
<tr>
<td>c (knee-Hip)</td>
<td>515.405</td>
</tr>
<tr>
<td>d (Hip-L1)</td>
<td>671.275</td>
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</tbody>
</table>

**Position mass centrum Frame 200**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>x-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (Toe-ankle)</td>
<td>0.360</td>
</tr>
<tr>
<td>b (ankle-knee)</td>
<td>181.160</td>
</tr>
<tr>
<td>c (knee-Hip)</td>
<td>535.165</td>
</tr>
<tr>
<td>d (Hip-L1)</td>
<td>774.665</td>
</tr>
</tbody>
</table>

**Distance 230-215 (Δd)**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>in meters</th>
<th>x-direction</th>
<th>in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A z-direction</td>
<td>0.780</td>
<td>0.00078</td>
<td>A x-direction</td>
</tr>
<tr>
<td>B z-direction</td>
<td>10.305</td>
<td>0.010305</td>
<td>B x-direction</td>
</tr>
<tr>
<td>C z-direction</td>
<td>-5.795</td>
<td>-0.005795</td>
<td>C x-direction</td>
</tr>
<tr>
<td>D z-direction</td>
<td>-42.890</td>
<td>-0.04289</td>
<td>D x-direction</td>
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</tbody>
</table>

**Distance 215-200 (Δd)**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>in meters</th>
<th>x-direction</th>
<th>in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A z-direction</td>
<td>0.52</td>
<td>0.00052</td>
<td>A x-direction</td>
</tr>
<tr>
<td>B z-direction</td>
<td>2.825</td>
<td>0.002825</td>
<td>B x-direction</td>
</tr>
<tr>
<td>C z-direction</td>
<td>-13.965</td>
<td>-0.013965</td>
<td>C x-direction</td>
</tr>
<tr>
<td>D z-direction</td>
<td>-60.5</td>
<td>-0.0605</td>
<td>D x-direction</td>
</tr>
</tbody>
</table>

**Speed(after)=d/t (215-230)**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>A x-direction</th>
<th>in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A z-direction</td>
<td>0.005</td>
<td>A x-direction</td>
</tr>
<tr>
<td>B z-direction</td>
<td>0.069</td>
<td>B x-direction</td>
</tr>
<tr>
<td>C z-direction</td>
<td>-0.039</td>
<td>C x-direction</td>
</tr>
<tr>
<td>D z-direction</td>
<td>-0.286</td>
<td>D x-direction</td>
</tr>
</tbody>
</table>

**Speed(before)=d/t (200-215)**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>A x-direction</th>
<th>in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A z-direction</td>
<td>0.003</td>
<td>A x-direction</td>
</tr>
<tr>
<td>B z-direction</td>
<td>0.019</td>
<td>B x-direction</td>
</tr>
<tr>
<td>C z-direction</td>
<td>-0.093</td>
<td>C x-direction</td>
</tr>
<tr>
<td>D z-direction</td>
<td>-0.403</td>
<td>D x-direction</td>
</tr>
</tbody>
</table>

**Acceleration=(Speed(after)-Speed(before))/t**

<table>
<thead>
<tr>
<th>z-direction</th>
<th>A x-direction</th>
<th>in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A z-direction</td>
<td>0.013</td>
<td>A x-direction</td>
</tr>
<tr>
<td>B z-direction</td>
<td>0.332</td>
<td>B x-direction</td>
</tr>
<tr>
<td>C z-direction</td>
<td>0.363</td>
<td>C x-direction</td>
</tr>
<tr>
<td>D z-direction</td>
<td>0.783</td>
<td>D x-direction</td>
</tr>
</tbody>
</table>
Appendix E

Biomechanical Calculations

Frame 215 Segment a (foot to ankle)

\[ F_{Az} = 181,933 \text{ [N]} \]
\[ F_{fx} = 634,074 \text{ [N]} \]
\[ \dot{a}_{Ax} = 0,013 \text{ [m/s}^2] \]
\[ m_A = 0,796 \text{ [kg]} \]
\[ a_{Ax} = 0,047 \text{ [m/s}^2] \]
\[ g = 9,81 \text{ [m/s}^2] \]
\[ F_{Ax} = 181,970 \text{ [N]} \]
\[ F_{Az} = 641,893 \text{ [N]} \]

\[ \Sigma F_x = ma \]
\[ F_{Ax} - F_{fx} = m_A \dot{a}_{Ax} \]
\[ F_{Ax} = F_{fx} + m_A \dot{a}_{Ax} = 181,933 + 0.796 \times 0.047 = 181,970 \text{ [N]} \]

Frame 215 Segment b (ankle to knee)

\[ F_{Kz} = 641,893 \text{ [N]} \]
\[ F_{Kx} = 181,970 \text{ [N]} \]
\[ m_K = 3,203 \text{ [kg]} \]
\[ a_{Kx} = 1,282 \text{ [m/s}^2] \]
\[ a_{Kz} = 0,332 \text{ [m/s}^2] \]
\[ g = 9,81 \text{ [m/s}^2] \]
\[ F_{Kx} = 186,077 \text{ [N]} \]
\[ F_{Kz} = 674,378 \text{ [N]} \]

\[ \Sigma F_z = ma \]
\[ F_{Kz} - F_{Az} - m_K g = m_K \dot{a}_{Kz} \]
\[ F_{Kz} = m_K \dot{a}_{Kz} + F_{Az} + m_K g = 3,203 \times 0.332 + 641,893 + 3,203 \times 9.81 = 674,378 \text{ [N]} \]
Frame 215  Segment c (knee to hip)

\[ F(Kx) = 186,077 \ [N] \]
\[ F(Kz) = 674,378 \ [N] \]
\[ m(H) = 7,036 \ [kg] \]
\[ a(Hx) = 2,084 \ [m/s^2] \]
\[ a(Hz) = 0,363 \ [m/s^2] \]
\[ g = 9,81 \ [m/s^2] \]
\[ F(Hx) = ? \]
\[ F(Hz) = ? \]

\[ \Sigma F_x = ma \]
\[ F(Hx) - F(Kx) = m(H)a(Hx) \]
\[ F(Hx) = F(Kx) + m(H)a(Hx) = 186,077 + 7,036 \times 2,084 = 200,740 \ [N] \]

\[ \Sigma F_z = ma \]
\[ F(Hz) - F(Kz) - m(H)g = m(H)a(Hz) \]
\[ F(Hz) = m(H)a(Hz) + F(Kz) + m(H)g = 7,036 \times 0,363 + 674,378 + 7,036 \times 9,81 = 745,995 \ [N] \]

Frame 215  Segment b (ankle to knee)

\[ F(Hx) = 200,740 \ [N] \]
\[ F(Hz) = 745,995 \ [N] \]
\[ m(L) = 9,556 \ [kg] \]
\[ a(Lx) = 1,759 \ [m/s^2] \]
\[ a(Lz) = 0,783 \ [m/s^2] \]
\[ g = 9,81 \ [m/s^2] \]
\[ F(Lx) = ? \]
\[ F(Lz) = ? \]

\[ \Sigma F_x = ma \]
\[ F(Lx) - F(Hx) = m(L)a(Lx) \]
\[ F(Lx) = F(Hx) + m(L)a(Lx) = 200,740 + 9,556 \times 0,783 = 208,222 \ [N] \]

\[ \Sigma F_z = ma \]
\[ F(Lz) - F(Hz) - m(L)g = m(L)a(Lz) \]
\[ F(Lz) = m(L)a(Lz) + F(Hz) + m(L)g = 9,556 \times 0,783 + 745,995 + 9,556 \times 9,81 = 847,222 \ [N] \]
Appendix F

Table: Percentages of total body mass (female)

Test subjects total mass: 588 N (ca 59.9 kg)

<table>
<thead>
<tr>
<th>Segment</th>
<th>%</th>
<th>mass (N)</th>
<th>(calculations)</th>
<th>mass (kg)</th>
<th>(calculations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>1.33</td>
<td>7.820</td>
<td>(=588*0.0133)</td>
<td>0.796</td>
<td>(=0.7820/9.82)</td>
</tr>
<tr>
<td>Leg</td>
<td>5.35</td>
<td>31.458</td>
<td>(=588*0.0535)</td>
<td>3.203</td>
<td>(=31.458/9.82)</td>
</tr>
<tr>
<td>Thigh</td>
<td>11.75</td>
<td>69.090</td>
<td>(=588*0.1175)</td>
<td>7.036</td>
<td>(=69.090/9.82)</td>
</tr>
<tr>
<td>Pelvis</td>
<td>15.96</td>
<td>93.845</td>
<td>(=588*0.1596)</td>
<td>9.556</td>
<td>(=93.845/9.82)</td>
</tr>
</tbody>
</table>
**Data processing**

Example how the angle for the hip flexion was calculated. This is for Frame 200-230.

<table>
<thead>
<tr>
<th>Frame</th>
<th>Knee-Hip</th>
<th>Hip-L1</th>
<th>Total ang Deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>KH_angRad</td>
<td>KH_angDeg</td>
<td>HL1_angRad</td>
<td>HL1_angDeg</td>
</tr>
<tr>
<td>200</td>
<td>1.385</td>
<td>79.366</td>
<td>1.059</td>
</tr>
<tr>
<td>201</td>
<td>1.368</td>
<td>78.361</td>
<td>1.074</td>
</tr>
<tr>
<td>202</td>
<td>1.350</td>
<td>77.334</td>
<td>1.099</td>
</tr>
<tr>
<td>203</td>
<td>1.333</td>
<td>76.373</td>
<td>1.120</td>
</tr>
<tr>
<td>204</td>
<td>1.316</td>
<td>75.390</td>
<td>1.141</td>
</tr>
<tr>
<td>205</td>
<td>1.297</td>
<td>74.343</td>
<td>1.164</td>
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<tr>
<td>206</td>
<td>1.278</td>
<td>73.258</td>
<td>1.183</td>
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<tr>
<td>207</td>
<td>1.260</td>
<td>72.188</td>
<td>1.206</td>
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<td>208</td>
<td>1.245</td>
<td>71.354</td>
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<td>209</td>
<td>1.226</td>
<td>70.241</td>
<td>1.253</td>
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<tr>
<td>210</td>
<td>1.208</td>
<td>69.191</td>
<td>1.278</td>
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<td>211</td>
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<td>68.109</td>
<td>1.301</td>
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<td>212</td>
<td>1.169</td>
<td>66.991</td>
<td>1.319</td>
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<td>213</td>
<td>1.150</td>
<td>65.892</td>
<td>1.342</td>
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<td>1.133</td>
<td>64.906</td>
<td>1.358</td>
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<td>215</td>
<td>1.115</td>
<td>63.881</td>
<td>1.377</td>
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<td>1.391</td>
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<td>60.657</td>
<td>1.418</td>
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<td>219</td>
<td>1.042</td>
<td>59.707</td>
<td>1.430</td>
</tr>
<tr>
<td>220</td>
<td>1.024</td>
<td>58.703</td>
<td>1.441</td>
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<tr>
<td>221</td>
<td>1.008</td>
<td>57.733</td>
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<tr>
<td>222</td>
<td>0.989</td>
<td>56.688</td>
<td>1.460</td>
</tr>
<tr>
<td>223</td>
<td>0.971</td>
<td>55.625</td>
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</tr>
<tr>
<td>224</td>
<td>0.951</td>
<td>54.488</td>
<td>1.471</td>
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<td>225</td>
<td>0.933</td>
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</tr>
<tr>
<td>230</td>
<td>0.863</td>
<td>49.437</td>
<td>1.505</td>
</tr>
</tbody>
</table>
I am a positive, energetic and active woman that appreciates and grows in both theoretical and physical challenges.