KTH Royal Institute of Technology

Biomechanics of Human Movement

SG2804

Project 1

Kinematics and inverse dynamics analyses of gait and jump take-off

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Contents

1 Introduction

In this report the lower body movement pattern of a healthy male specimen is analyzed. Using data collected from the KTH MoveAbility lab, the lower body joint angles, moments and powers are computed in the sagittal plane for three different cases: normal walk, high jump and low jump. The right and left gait cycles are described and compared for the normal gait pattern, and the low and high jump take-off are described and compared using data from the right limbs.

2 Methods

In this section the methods used to compute the angles, moments and powers are described. The complete version of the MATLAB code where this logic is implemented can be found on the appendix.

2.1 Inverse Kinematics

Coordinate data from the measurements is loaded using the MATLAB code provided on Canvas platform [2]. The data provides the position of the markers in each frame in the $y - z$ plane, as well as ground reaction forces and COP position, relative to a common reference system.

Firstly, the lower-body segments are modeled as position vectors in the $y-z$ plane. This is done by taking the difference of the position (given by the marker's coordinates) of the distal and proximal joints to the segment, in the y and z directions. Then, the angles of the segments are computed by simple trigonometry, as in Eq. 2. The computations are executed for all the frames in the dataset.

$$\theta_{seg} = tan^{-1}\left(\frac{r_{seg,y}}{r_{seg,z}}\right) \tag{1}$$

Where:

θ_{seg} = angle of the segment relative to z direction;

$v_{seg,y}$ = component of the segment vector in the y direction;

$v_{seg,z}$ = component of the segment vector in the z direction;

Segment angles are therefore defined as the angle of the segment relative to the z direction. The segments analysed are: foot, shank, thigh, pelvis and trunk. The *atan2d* function returns values in degrees for the closed interval [-180,180], therefore no discontinuities have to be corrected due to the angle range. Then, the relative or joint angles of the ankle, knee and hip are computed by subtracting the angle of the segment proximal to the joint from the angle of the segment distal to the joint. A correction factor is added if needed, to match the reference system described required. Figure shows the segments and angles, as well as the reference system ans sign conventions.

From the array of angles, the angular velocities and accelerations are computed for the segments and the joints. Those will be needed later in the inverse dynamics calculations. An agnostic function is implemented to get the first and second derivatives of any given array. The MATLAB function *gradient* is used for the computation. The time step in seconds between data points corresponds to $1/F_s$, where the sample frequency equals 100Hz. Data is trimmed to the correct frames for each gait cycle after the numerical computation of he derivatives, otherwise the data for the first and last frames becomes just an approximation. An agnostic function that plots any 2 given arrays to normalized $x - axis$ is implemented and used to plot the joint angles of the ankle, knee and hip, as well as the segment angles of the pelvis and trunk. The axis names and title are given as inputs to allow reuse of the function.

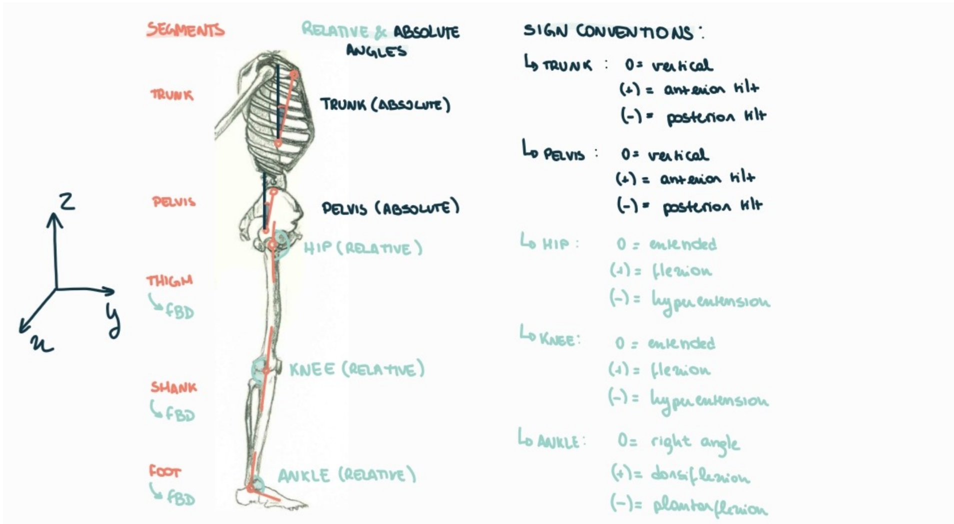


Figure 1: Representation of the segments, angles and reference system.

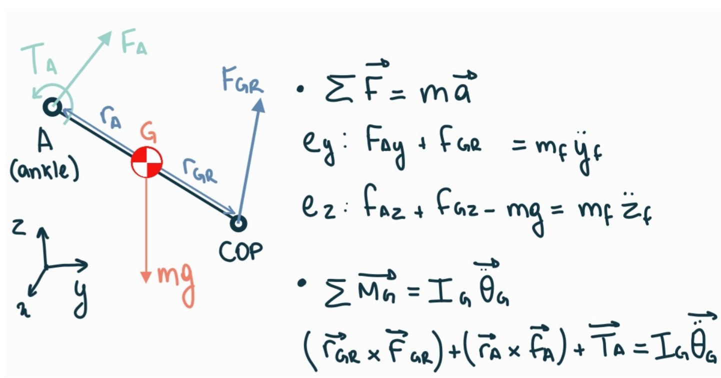


Figure 2: Free body diagram of the foot segment, with the representation of the external moments and forces acting in the foot system and the equations used to calculate joint forces and moments.

2.2 Inverse Dynamics

The next step is the calculation of internal joint moments and powers. To compute joint moments, a free-body-diagram analysis is performed, segment by segment. Figure 2 shows an example for the foot segment.

Working on 2D, Newton's second law yields 2 equations for balancing forces: one in the y direction and one in the z direction, as seen in figure 2. Those can be solved to obtain the 2D components of the joint reaction force F_A acting at point A. Then, Newton's second law for rotation is applied at point G (COM). Balancing moments around point G yields one more equation (also seen in the figure) that can be solved for the moment in point A (ankle joint), which is the internal joint moment of the ankle.

To solve the equations, anthropometry constants have to be set. Those are: segment length, mass, moment of inertia and COM position relative to proximal joint position. The segment length is firstly calculated using Winter's anthropometry table [4], which gives approximations relative to the person's height. This approximation, however, does not account for the inaccuracy between joint position and marker position. In an attempt to minimize the error, a function is implemented on MATLAB to get the length in the first frame of each gait cycle, and average between left and right sides is used to give one single length value per limb. The fact that the movement is actually measured in 3D will introduce an error in this value. However, since the length is used only to compute the moment of inertia, this error is negligible.

The equations to approximate segment relative masses, moment of inertia and COM position are all taken from Winter's anthropometry table. A function to compute the COM position frame-by-frame is implemented by taking the position of the proximal and distal joints and the COM position relative to proximal joint from Winter's table. The computation for each frame follows Eq. 2.

$$\vec{r}_{COM} = \vec{r}_{proximal} + (\vec{r}_{distal} - \vec{r}_{proximal}) \cdot d_{COM} \tag{2}$$

Where:

$\vec{r}_{COM}$ = position vector of the segment center of mass;

$\vec{r}_{proximal}$, $\vec{r}_{distal}$ = position vector of the proximal and distal joints;

$dCOM$ = center of mass/ segment length relative to proximal joint [4];

The joint moment computation also requires the calculation of $\vec{r}_A$ and $\vec{r}_{GR}$, which are the vectors from point G to the point of application of the forces. Those are computed by simple geometry, by subtracting the y and z coordinates. The center of pressure position in the y direction is used to calculate $\vec{r}_{GR}$, while the z component of the COP is zero.

The linear acceleration of the segment COM is computed by taking the second derivative of the COM position, using the same function implemented to calculate the angular acceleration of the segments and joints. Since the ground reaction force is measured, it is possible to solve the forces equations and find the joint reaction force acting at point A. This is the reason why the analysis has to be performed bottom-up. Then, the computed joint forces are used in to calculate the joint moment. To guarantee consistency on computations with vectors, the MATLAB cross product function is used to compute the moments in the x direction. Since the function requires a 3D array as an input, all the arrays are converted to 3D by adding a column of zeros in the x direction. Therefore, the joint moment around the x axis can be computed. Hip extensor moment, knee extensor moment and ankle plantarflexor moment are defined as positive.

The exact same methodology is applied to the next segment, the shank. Now, the unknowns are the contact forces and moment at the proximal joint, in this case the knee. However, the contact forces at the distal joint (in this case, the ankle) are known - they are equal to minus the forces and moment calculated at the foot, which is direct application of Newton's third law.

Finally, the joint powers are calculated with Eq. 3. Positive values of power represent power generation, while negative values represent power absorption. All the data is normalized to the gait cycle to allow the comparison of right and left motions.

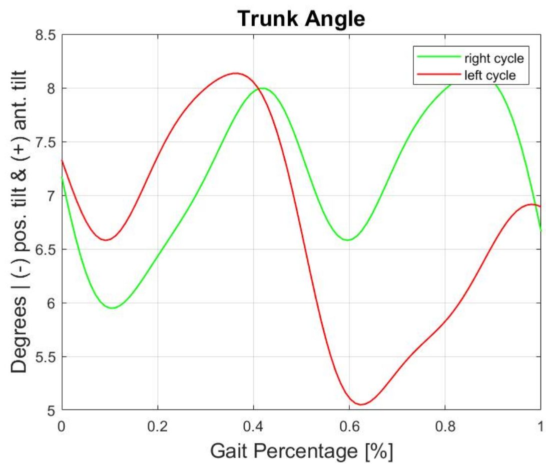
$$P_{joint} = \vec{M}_{joint} \cdot \vec{\omega}_{joint} \tag{3}$$

With minor changes, the code (.m file attached) can be used to compare any set of motion data. Therefore, the same code is used to analyze the low vs. high jump. Motion data from the right limbs is loaded and the 2 jumps are compared by normalizing each jump cycle over the duration of the jump.

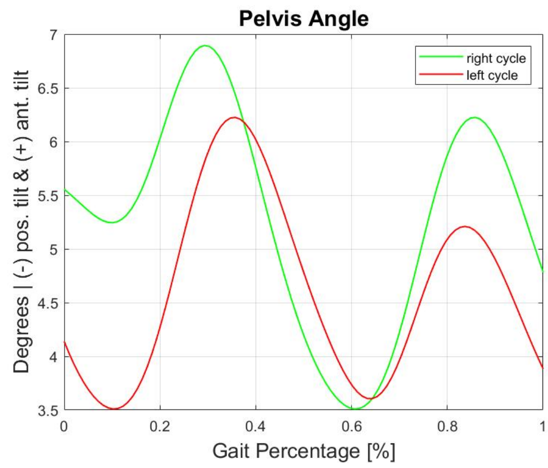
3 Results

3.1 Walking

The pelvis and trunk absolute angles during a normal gait cycle are illustrated by the graphs in figure 3 below. The relative angles, moments and powers of the joints are presented in figures 4, 5 and 6. Right limbs are shown for the right cycle, while left limbs are shown for the left cycle. Data is normalized to gait cycle.

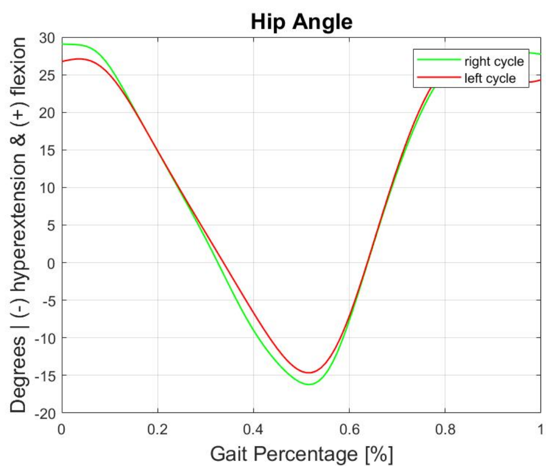


(a) Trunk angle.

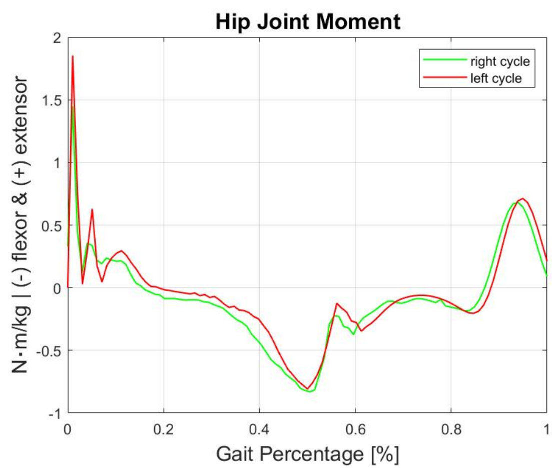


(b) Pelvis angle.

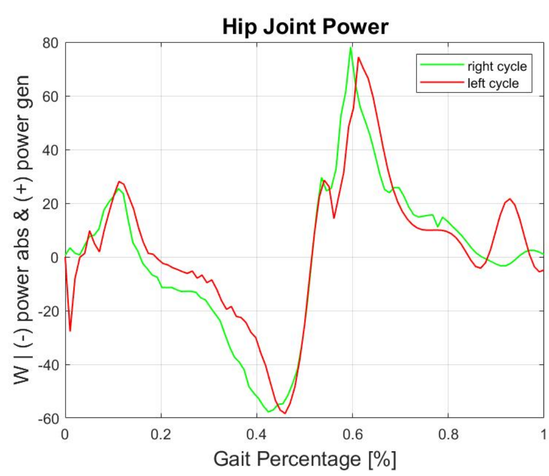
Figure 3: Sagittal plane angles



(a) Hip angle.

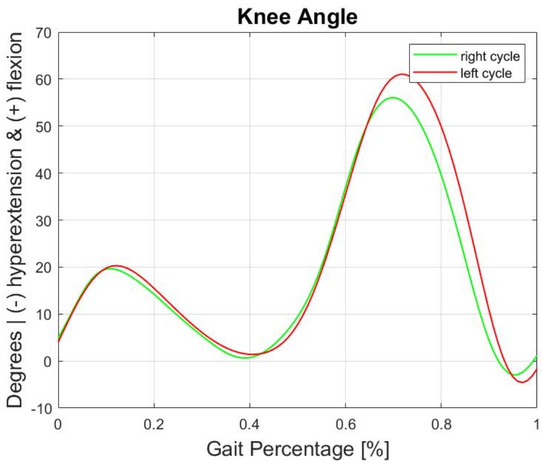


(b) Hip moment.

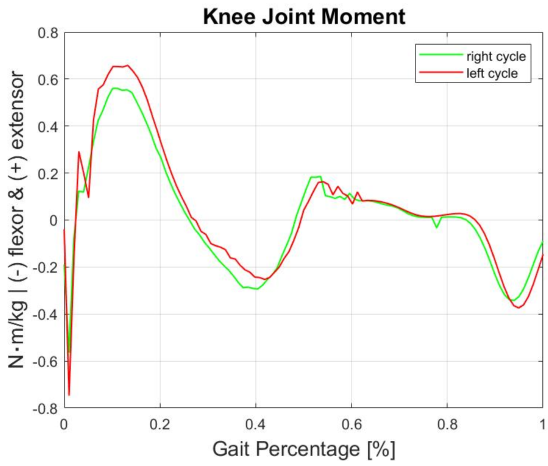


(c) Hip power.

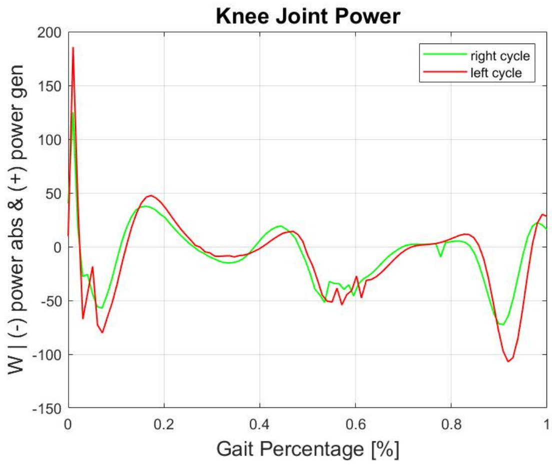
Figure 4: Angle, moment and power for the hip.



(a) Knee angle.

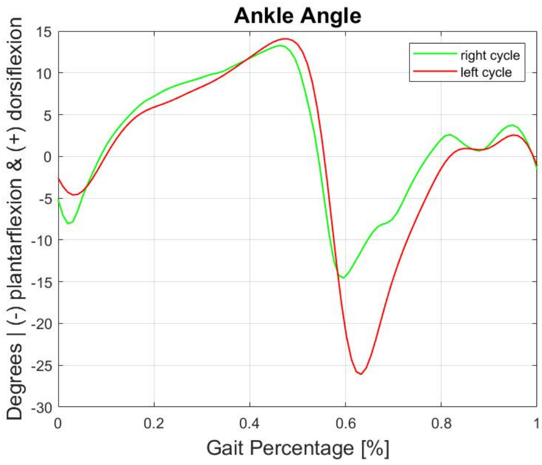


(b) Knee moment.

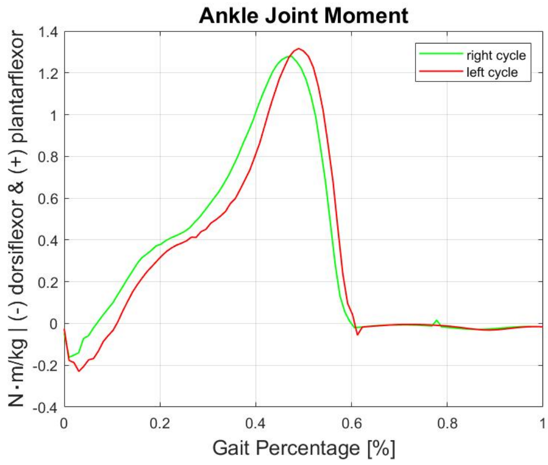


(c) Knee power.

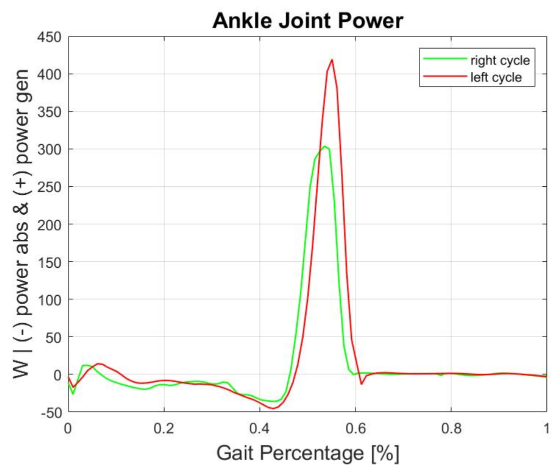
Figure 5: Angle, moment and power for the knee.



(a) Ankle angle.



(b) Ankle moment.

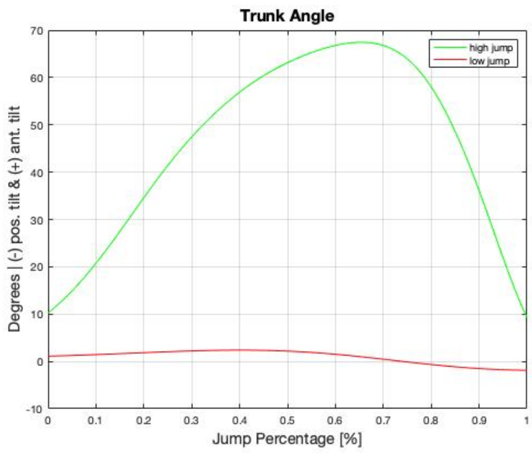


(c) Ankle power.

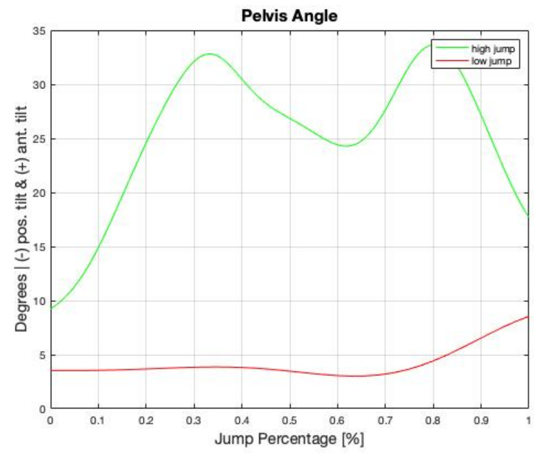
Figure 6: Angle, moment and power for the ankle.

3.2 Jump take off low vs high

The pelvis and trunk absolute angles during low and high jump take-off are illustrated by the graphs in Figure 7 below. The relative angles, moments and powers of the joints are presented in figures 4, 5 and 6. Right limbs are shown for both jumps. Data is normalized to jump cycle.

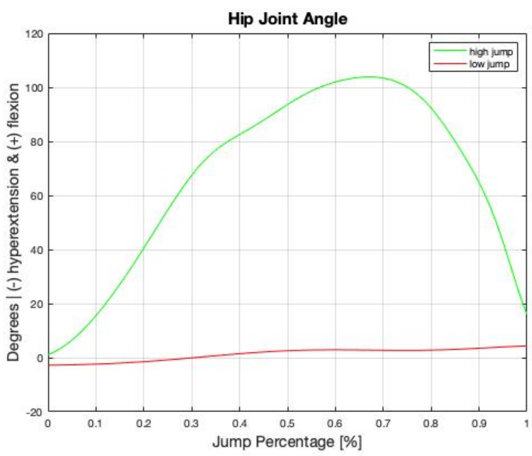


(a) Trunk angle during jumping

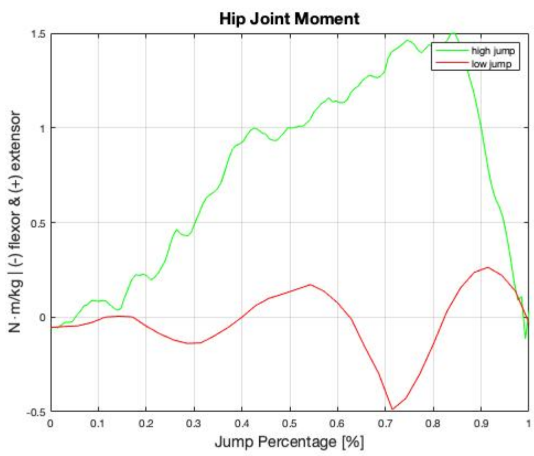


(b) Pelvis angle during jumping

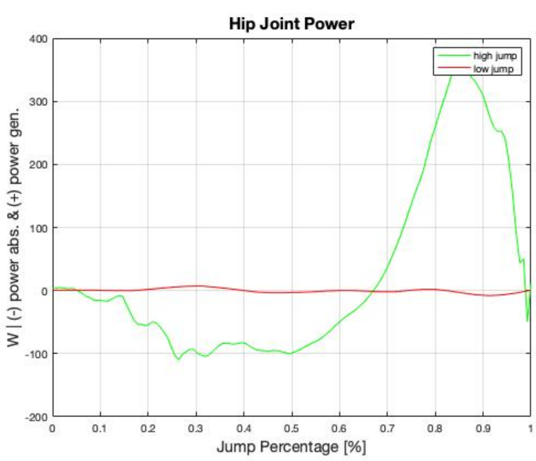
Figure 7: Sagittal plane angles during jumping



(a) Ankle hip joint during jumping.

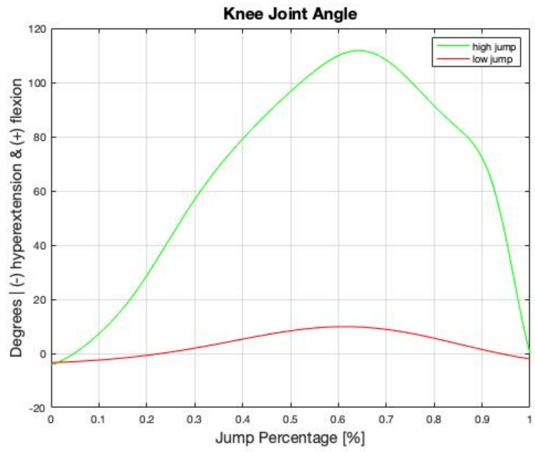


(b) Hip joint moment during jumping.

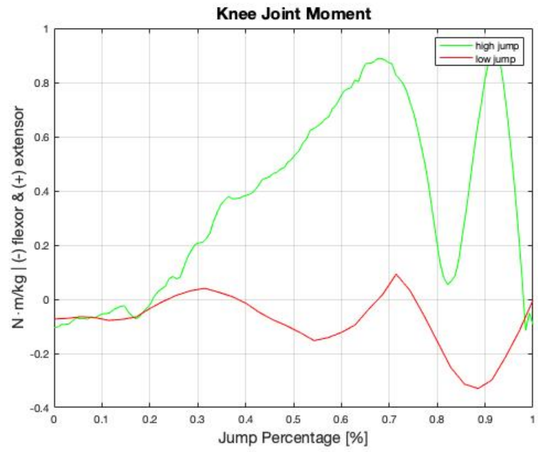


(c) Hip power during jumping.

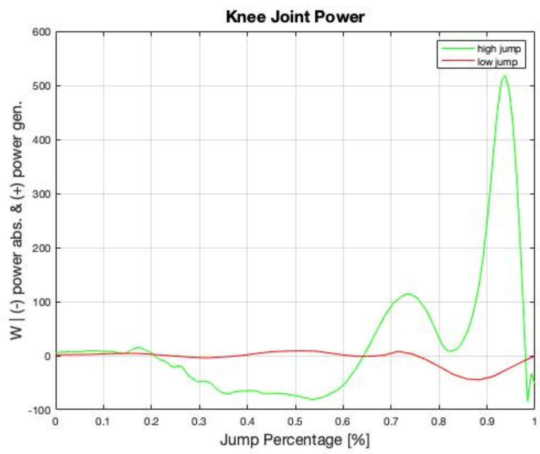
Figure 8: Results for the hip during jumping



(a) Knee joint angle during jumping.

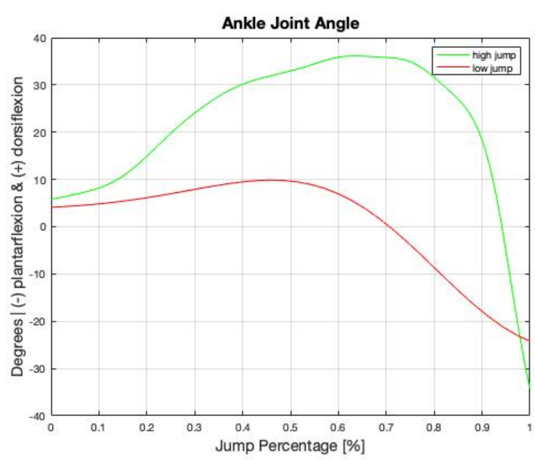


(b) Knee joint moment during jumping.

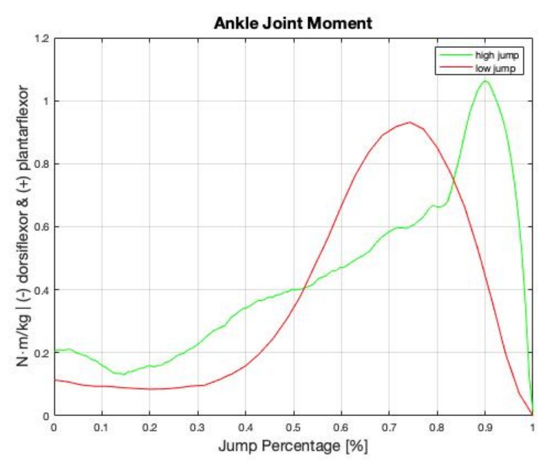


(c) Knee joint power during jumping.

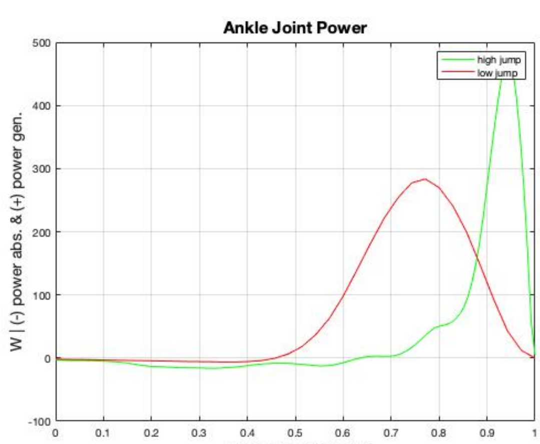
Figure 9: Results for the knee during jumping



(a) Ankle joint moment during jumping



(b) Ankle joint moment during jumping.



(c) Ankle joint power during jumping.

Figure 10: Results for the ankle during jumping

4 Discussion

4.1 Walking

The whole gait cycle is composed of a stance phase and a swing phase. Stance makes up about 60 % [3] of the cycle and during this time the foot has contact with the ground. The swing phase follows after toe-off which can be seen in figure 6a where the plantarflexion of the ankle reaches a peak at just over 60 percent of the gait cycle. To determine whether the muscle activity is concentric, isometric or eccentric, the angles (or more specifically the angular velocities which can be seen as the slope of the angle graphs) moments and powers in figures 4, 5 and 6 are put in relation to each other and the results are compared the lecture notes [1] that lists all muscles activated during the gait. Since all muscles pull, positive moments in e.g. the knee (extensor) will have to be generated by muscles that extend the knee.

Starting with the hip, it is possible to determine the muscle activation type by first looking at the angle in figure 4, which is at its maximum at heel strike. For the first 20% the moment and power are positive, implying that the hip extensors are contracting concentrically. Between 20-50% the moments and powers are negative meaning that the hip flexors are contracting eccentrically. As the gait enters the swing cycle the angle increases and the "spring energy" that has been loading up in the hip flexors during the gait is now released as a concentric contraction. The last peak in the cycle is an eccentric contraction of the hip extensors that decelerates the leg.

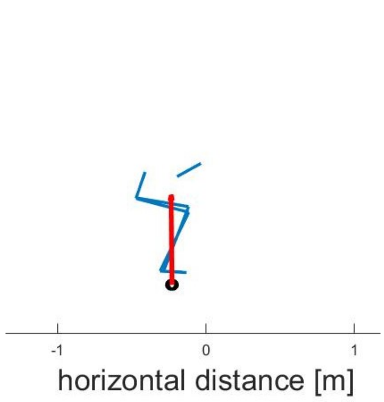
The first peak in figure 5 is neglected since it is most likely caused by an error and, thereby, does not add any value to the analysis. With that exception the cycle starts with a positive moment and negative power generation which implies eccentric contraction of the knee extensors. Between 15% and 40% of the cycle, the knee is extending while the moment and power goes from positive to negative. This implies that the contraction goes from a concentric to an eccentric contraction of the knee extensors. The knee is then flexed until toe-off, first by a concentric contraction of the knee flexors and then through eccentric contraction of the knee extensors. The last part of the knee flexion before toe-off occurs with the help of the ankle and the Soleus. For the swing phase, muscle activity is low until the knee flexors contract eccentrically as the knee straightens before the next heel-strike.

The same reasoning is applied for the ankle, presented in figure 6, which plantarflexes a few degrees during the heel rocker. Since the moment is negative during this first part, and thus dorsiflexes the ankle, that means that the Tibialis Anterior is contracting eccentrically. As the gait proceeds to single support the ankle angle dorsiflexes while the moment is instead trying to plantarflex it. Again the contraction is eccentric but now it is the ankle extensors, such as the Soleus and Gastrocnemius, that does the work. This agrees with the power graph which has been close to zero or negative up until now. The rapid change in ankle angle at about half the cycle can be explained by high ankle moment together with the power peak. It is still the ankle extensors that are activated but the power curve implies that the contraction is now concentric. The gait is now in the swing phase meaning that, apart from a small dorsiflexing moment produced by the Tibialis Anterior, the foot is in the air and the moment and power is zero.

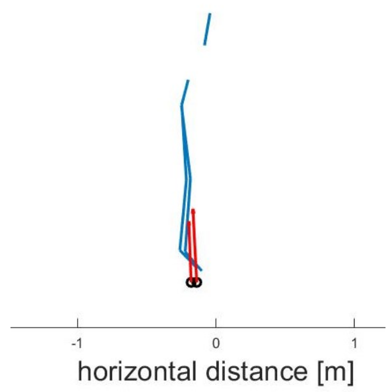
Regarding the symmetry of the kinetics and kinematics figures 3, 4, 5 and 6 shows that this specimen is quite symmetric for the most part with some exceptions. The visually significant differences in the pelvis and trunk angle plots are actually quite small noticing the scale. The ankle plantarflexion at toe-off is bigger on the left cycle. Power generated in the left ankle is higher than for the right cycle. This means that the push off is more significant on the left than right cycle, and results in a slightly higher knee flexion on the left side, right after toe-off. The knee power absorption in the end of the swing phase, when the knee extension is decelerated, is also slightly bigger on the left cycle. Its is previously known that the specimen has long been a soccer player, which might be the reason why both sides have minor differences. However, those differences are among the spectrum of the normal gait.

4.2 Jump take-off low vs. high

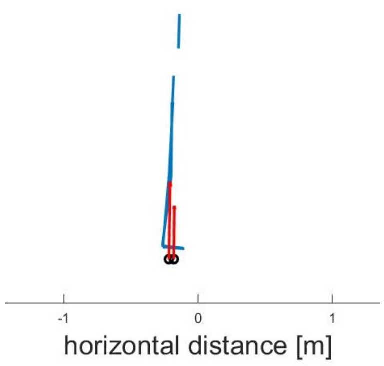
The high jump can be described as a squat with a "folding" of the upper body (preparatory phase) followed by a rapid extension of the body (propulsive phase), which starts at around



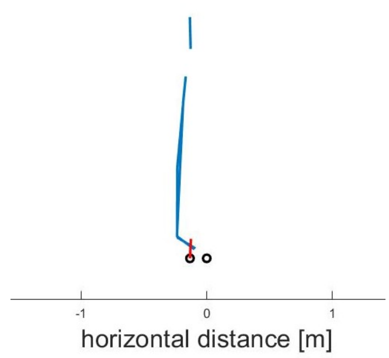
(a) End of preparatory phase on high jump



(b) End of propulsive phase on high jump



(c) End of preparatory phase on low jump



(d) End of propulsive phase on low jump

Figure 11: Stick figures representing the low and high jumps.

60% to 70% of the jump cycle, ending with the lift-off from the ground, when the foot loses contact with the ground and the ground reaction drops to zero. The maximum angles follow the sequence hip-knee-ankle. The whole movement takes approximately 1.3s. Meanwhile the low jump has no observable preparatory phase, and it's visually mainly driven by the ankle joint. The propulsive phase starts at about 50% of the jump cycle. The whole movement takes about 0.35s to happen, however, the data is normalized to allow comparison. Figure 11 presents the "stick figures" provided by the MATLAB code in [2] of the end of preparatory phase (defined here as the time when the angles change direction and the angular speeds are therefore zero) and the end of propulsive phase (start of lift-off, when ground reaction drops to zero) for low and high jumps.

At the ankle joint, the high jump cycle starts with a dorsiflexion, correspondent to the preparatory position on a half-squat. At approximately .7 of the jump cycle the preparatory phase ends, the angular velocity drops to zero and the movement starts to go on the other direction at the propulsion phase, now plantarflexing. The moment is plantarflexor (positive) during the whole preparatory phase, even though the ankle is dorsiflexing, because the plantarflexor muscles contract eccentrically to decelerate the descent of the body. This explains why, in the ankle joint power graph, the power has a negative (meaning power absorption) value during the preparatory phase. That value is, however, small, because the magnitudes of the angular velocity and joint moment are also small. At the propulsive phase, the ankle plantarflexor moment rapidly reaches a peak while the ankle joint is plantarflexing. As a result, the power generation also reaches a peak. That characterizes well the rapid and powerful extension of the jump. During the propulsive phase, the plantarflexors contract concentrically and perform work to rapidly extend the ankle joint. The high peak in the plantarflexor moment is probably due to the combined activation of the soleus and the gastrocnemius contributing to the power generation to lift the body off the ground. After the body reaches it's peak acceleration upwards and therefore peak ground reaction force, the ground reaction force rapidly drops, and so do the joint moments and powers.

Meanwhile, in the low jump, the lack of the preparatory phase explains why the dorsiflexion is less than 5 degrees and the moment and power are nearly neglegible before the propulsion starts. During the propulsive phase, the ankle joint is plantarflexing while the moment is plantarflexor, which characterizes the concentric contraction of the plantarflexor muscles. The work performed to lift the body's center of mass is mainly due to the concentric contraction of the plantarflexor group.

The low jump curves are less steep and the peaks are smaller. This is expected since the movement is way more timid and the range of motions are smaller. However, it is noticeable that of the 3 joint analysed, the ankle joint is by far the one where the differences between both motions is less pronounced. This is due to the fact that the ankle plantarflexion is the main driver of the movement in the low jump.

At the knee joint, the high jump movement starts with a knee flexion, as shown in Figure 9a. The knee extensors (quadriceps group) performs an eccentric contraction to control the descent of the body during the preparatory phase. Although the knee moment is extensor, the knee flexors (hamstrings) are also active in this phase, but their major role is related to the eccentric work at the hip joint, because some of those muscles are bi-articular and have both knee flexing and hip extension functions. The power seen in Figure 9c is negative (power absorption). When the preparatory phase is over and the propulsive phase begins, the knee starts to extend while the moment is extensor. This means that the knee extensors will contract concentrically and generate power. The joint power reaches a peak right before the take-off.

There is an interesting decrease in knee extensor moment right after the start of the propulsion phase. The angle of the knee extends in a near constant rate (i.e. constant angular velocity). The apparently most plausible hypothesis to explain this decrease is that, in the beginning of the propulsion, the extension work is mostly due to hip extension. Since the hip extensors are also knee flexors, this could result in a drop in knee extensor moment. The knee extensor moment starts to act in power generation further in the ascent, resulting in another peak in knee extensor moment, this time followed by a rapid increase in knee extension velocity.

For the low jump, due to the absence of the preparatory phase, the knee flexion in the beginning of the movement is very small, and a very small level of flexion is observable. Although the angles are quite small, the joint moments at the knee assume positive and negative values during the motion. Besides, one can feel the muscles contracting when performing a similar jump. Therefore, all the joint moments of the low jump are plotted on the same graph (Figure 12 to analyse the synergies between muscle function.

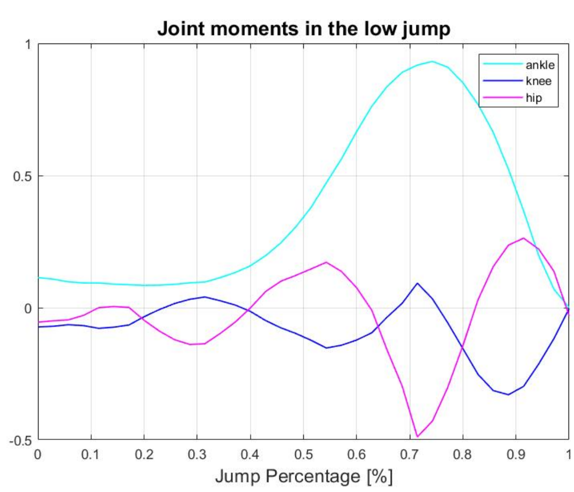


Figure 12: Joint moments for the low jump.

From the ankle analysis it is known that the ankle plantarflexors will have a major role in the movement. The Gastrocnemius will be active, and this muscle is also a knee flexor. This might contribute to the knee moment behaviour that can be seen in the figure 9b. The same effect of bi-articular muscle synergies happens in the hip joint, as it is illustrated in the Figure 12. The hip and knee moments will counteract each other during the whole low jump while the actual power production to lift off the body center of mass will come from what the ankle. The behaviour during propulsion can be explained by the concentric contraction of the Gastrocnemius, which has a knee flexing function. To maintain the leg straight though out propulsion, and the knee and hip flexors and extensors will become active in an almost isometric contraction, since no significant movement of the joint is observable.

At the hip joint, during the high jump, the same motion pattern is observed. During the preparatory phase, the hip flexes more than 90° while the hip joint moment is extensor. This characterizes a eccentric contraction of the hip extensor muscles, such as the hamstrings, controlling and decelerating the flexion of the hip until the body reaches the "folded" position. Consequentially, the power generation is negative during the descent. Some muscles of the hamstring complex are bi-articular and therefore also act as knee flexors. This might have a consequence in increasing the muscle activity of the knee extensors to compensate for that action during the descent. During the propulsion phase, the hip joint starts extending while the hip moment reaches its extensor peak. Therefore, the power generation is positive and rapidly reaches a peak when the ground reaction force is maximum. After the body reaches its peak acceleration upwards, the moment and power start to decrease.

The low jump has large differences in the motion pattern for the hip joint due to the lack of the hip flexion on the preparatory phase. The angle barely changes at the hip. However, the moments oscillates from flexion to extension, in a pattern similar to the one observed at the knee joint, as shown in figure 12 and discussed above. As mentioned before, this might be an effect of the synergies between bi-articular muscles, which creates joint moments in a chain reaction, from bottom up. On the low jump, the knee flexors and extensors, as well as the hip flexors and extensors, act in order to keep the body in a upright position during the jump.

5 Conclusion

5.1 Walking

Judging from the power graphs it it possible to conclude that the muscles involved in plantarflexion of the ankle joint are the most important for propelling the body during normal walk. That is the Soleus and Gastrocnemius. The muscles around the hip and knee joint also ads to the power generation that ultimately moves you forward but not to the same extent. The knee muscles are important to shock absorption. The hip keeps pelvis and trunk stable while progressing the body center of mass forward. Another important function of theirs is, of course, also to keep you upright and stable. Both flexors and extensor muscles groups play a role in the rockers, which are described in the literature as the major conditions for normal walking.

5.2 Jump take-off low vs. high

From the power graphs presented, it is possible to conclude that the extensor and plantarflexor chain is the most important for jumping. The highest amount of power produced during the high jump will be due to the concentric contraction of glutes and quadriceps, quadriceps and gastrocnemius. For the low jump will the largest power production instead appear around the ankle joint where Gastronemious and Soleus will be the muscles with largest impact. If the two different jumps are compared to each other, the majority of the power will be produced by the muscles around the ankle for the low jump, while it is more evenly divided between the muscles around three mentioned joints for the high jump.

6 Contribution

All group members has been committed to the task and contributed to calculations, matlab and writing of the report. The golden star does however go to Mariah who really excelled in all areas.

7 References

References

[1] Elena Gutierrez Farewik. Lecture 8 notes in Biomechanics of Human Movement. Nov. 2021.

[2] KTH Movability Lab. Project 1 support files. Nov. 2021. URL: https://canvas.kth.se/courses/27063/files?preview=4843254.

[3] Thomas K. Uchida and Scott L. Delp. Illustrations by David Delp. Biomechanics of movement. The MIT press, 2020.

[4] David A Winter. Biomechanics and motor control of human movement. John Wiley & Sons, 2009.