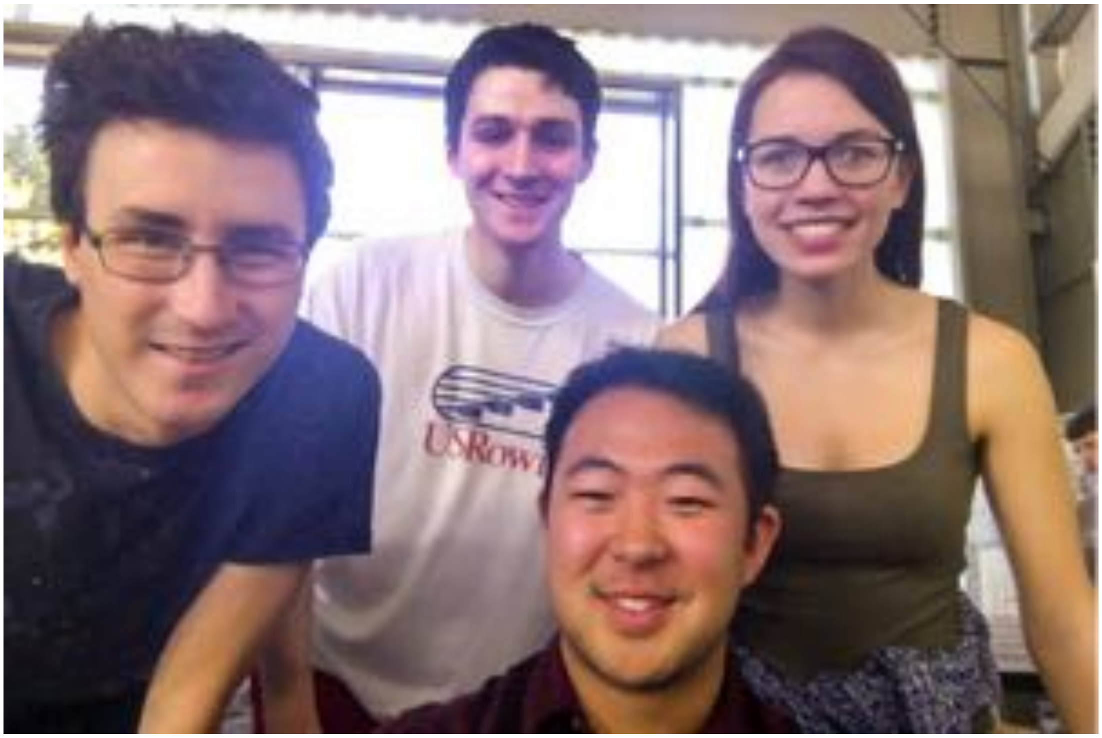


Rock N' Roo

ME 112

Team Açaí e mi

Claudia Brunner, Ben Chuter, Jin Park, Wiley Webb

March 15, 2016

1 Executive Summary

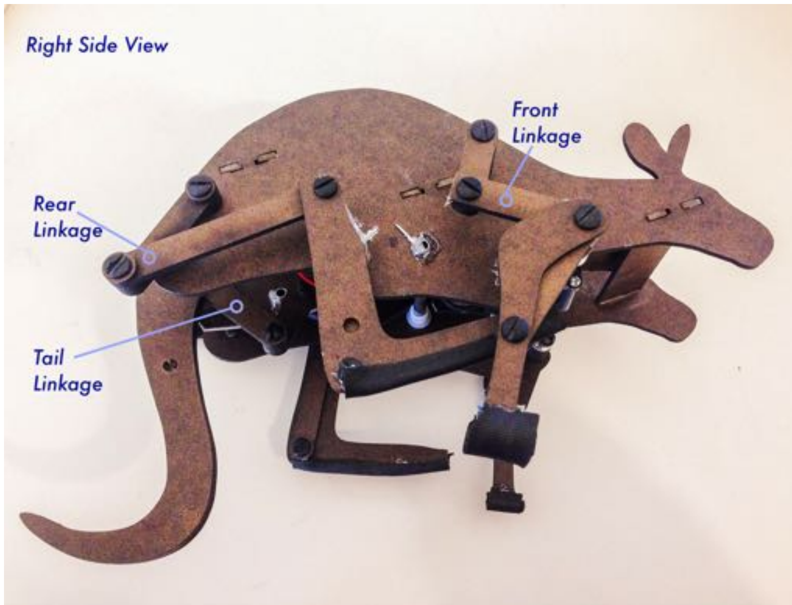


Figure 1: Our kangaroo.

Our team aspired to create a small autonomous walker that could effectively mimic the pentapedal gait of a kangaroo and reliably traverse a terrain of rough paving stone. Powered by a 3V battery pack that provided an effective voltage of 2.6V to a single Tamiya 6 Speed H. E. motor, our walker successfully crossed Meyer Circle, our test site. The motor was constructed with a transmission ratio of 196.7:1 and used a belt transmission system to power five 4-bar linkages representing forelimbs, hind limbs, and a tail, and accurately recreated pentapedal locomotion. Traveling at 11.2 cm/s, it overcame wet and windy conditions and maintained a straight course without intervention to reach the edge of the patio. Force plate analysis demonstrated that its force and power generation were proportional to those of a real kangaroo.

Our kangaroo walker's frame shape, limb placement, limb curves, and limb synchronization were all designed to closely mimic that of a biological kangaroo. We discovered that the kangaroo walker moved most effectively when these limbs were synchronized in a biomimetic manner. As a result, the force and power generation sequence of our kangaroo walker limbs in the vertical and fore-aft directions were highly biomimetic. To further improve our kangaroo, we would realign the two sides of the frame to improve symmetry and add compliance to the hind and fore limbs to smooth its gait and prevent it from turning.

Contents

2 Background

Inspired to create an autonomous walker worthy of a Disney Down-Under exhibit, we designed a biomimetic model kangaroo that could perform pentapedal locomotion and reliably travel across stone terrain at roughly 10cm/s. To succeed the walker had to be battery powered and maintain a straight course without outside intervention. Furthermore, we aimed to create a walker no taller than 0.35m tall and 0.35 m long while operating on a budget of 80 dollars.

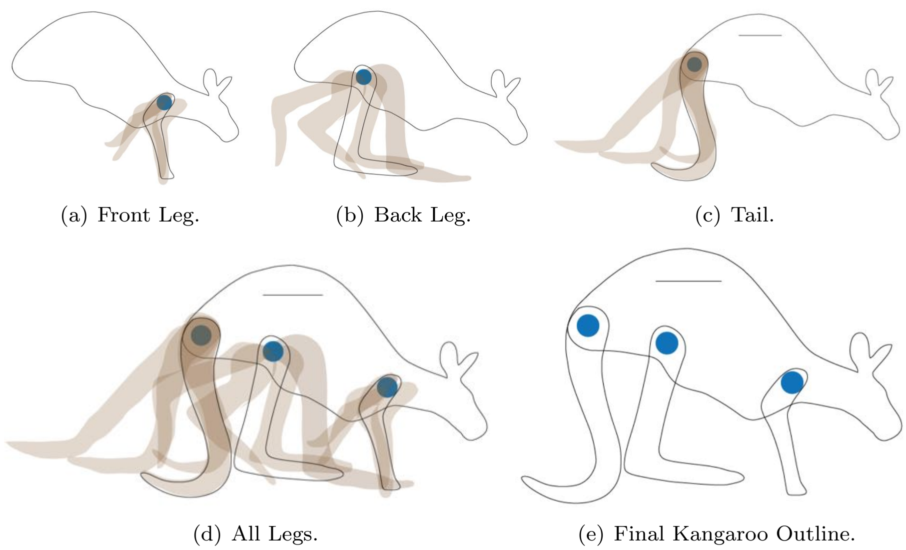
To achieve these goals, we chose frame dimensions of 0.27m in length and 0.15m in height and focused on ensuring that our walker's frame design, limb positioning, limb curves, and limb synchronization matched those of a living kangaroo. Ideally the frame would have the appearance of the kangaroo while providing a sufficient base on which the five 4-bar linkages could be constructed. The positioning of these 4-bar linkage limbs on the frame had to maintain suitable distances from each other such that the linkages would not interfere with each other while also matching the relative positions of a kangaroo's limbs to achieve biomimicry. The limb curves produced by these linkages also had to functionally propel the walker forward while staying true to the curves of a living kangaroo. Finally, we had to find a way to synchronize the limbs on their respective curves such that they would work in a coordinated fashion to achieve pentapedal motion while again maintaining a high degree of biomimicry. By keeping these design specifications as proportional to those of a biological kangaroo in the ways described above, we hoped to achieve a realistic kangaroo walker that successfully satisfied our design requirements.

3 Design Description

We designed our pentapedal walker to closely resemble a living kangaroo in its frame and limb design, curves, and synchronization. The frame shape and joint placement originated from overlaid traced silhouettes of a real kangaroo performing pentapedal motion. We similarly determined the desired limb curves by tracing the motion of the limb end points relative to the body. Using 4-bar linkage curve software, we designed appropriate 4-bar linkages that produced biomimetically favorable linkage curves for the forelimbs, hind limbs, and tail. Thus upon completion our kangaroo walker proved to resemble a biological kangaroo in terms of static appearance as well as the kinematics and kinetics of its pentapedal motion.

3.1 Frame

Final Frame Design As previously mentioned, for our second and final frame design, we analyzed the kangaroo in the movement video published by O'Conner et al. by taking screenshots of the kangaroo at various points in its gait and tracing the silhouette of the body, legs and tail. We then overlaid the silhouettes and determined an average shape and joint placement for each body part. The blue dots in the figures below indicate the approximate locations of the kangaroo's joints.



(a) Front Leg. (b) Back Leg. (c) Tail.

(d) All Legs. (e) Final Kangaroo Outline.

Figure 2: Our analysis of kangaroo body and leg silhouettes.

This approach enabled us to create a highly biomimetic kangaroo, but it also made functional sense to model physical shapes from a living kangaroo, as evolution had proven those shapes to be most effective. Furthermore, we had made a previous iteration that demonstrated that these limbs could effectively operate in the desired locations without interfering (Please see Appendix B). We noticed that the front and back legs barely changed their shape during the motion cycle, and merely rotated around the joint, so that they could easily be modeled as rigid bodies. However, the tail significantly changed its curvature; thus by using an average tail curvature we were able to create a functional rigid tail.

We chose to make the crank holes in the positions of the joints where the limbs seemed to rotate. The point with which the back limbs and the tail impacted the ground changed throughout the motion cycle, which meant that our locomotion cycle was difficult to exactly predict using a single coupler point. However, by identifying curves formed by the limb ends we were able to identify reasonably accurate potential curves. Furthermore, although challenging to model, by recreating similar limb shapes the coupler point changed on our walker in a similar way to that of a real kangaroo.

Figure 3: Horizontal connection of the kangaroo's two sides.

We joined the two halves of our kangaroo by 3.5" x 1" sections of duron. A 3.5" width provided a reasonably kangaroo-like length-to-width ratio while still providing enough space in which to fit the motor and output shafts. In the image above, the blue tape indicates where we later attached our motor so its output could directly power the forelimbs.

Figure 4: Our final kangaroo frame.

3.2 Power Transfer

The motor output shafts directly connected to the front shafts, which powered the crank of the forelimbs. Timing belts and pulleys transferred the output from the motor and forelimbs to the hind limbs and tail via pulleys that were fixed to the axles of all three linkage cranks. To fix the pulleys to the forelimbs and motor, we drilled holes through both the pulleys and forearm shafts. The shafts were connected to the crank arm of our forelimb linkage. We then aligned the holes on the forearm shafts, pulleys, and motor shaft, inserted pins through those holes, and secured the pins with glue. This process ensured that the forelimb pulleys and crankshafts exhibited the same angular speed as the motor. The pin connections also prevented the pulleys and forelimb shafts from sliding axially in relation to the motor output shaft. Pulleys were similarly fixed to the axles of the hind limb and tail cranks. The hind limb and forelimb pulleys were joined by a timing belt which extended down the right side of the kangaroo's underside. A longer timing belt on the left side joined the tail and forelimb pulleys.

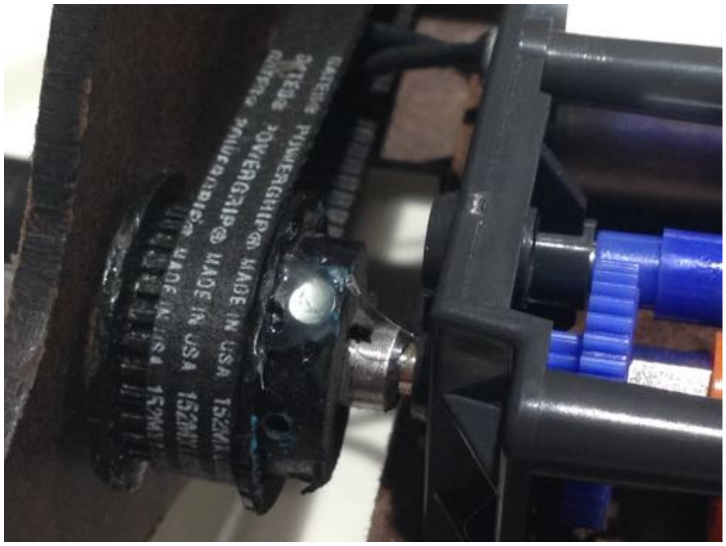


Figure 5: Pin connection that secures the forelimb pulleys to the forelimb shaft and motor output

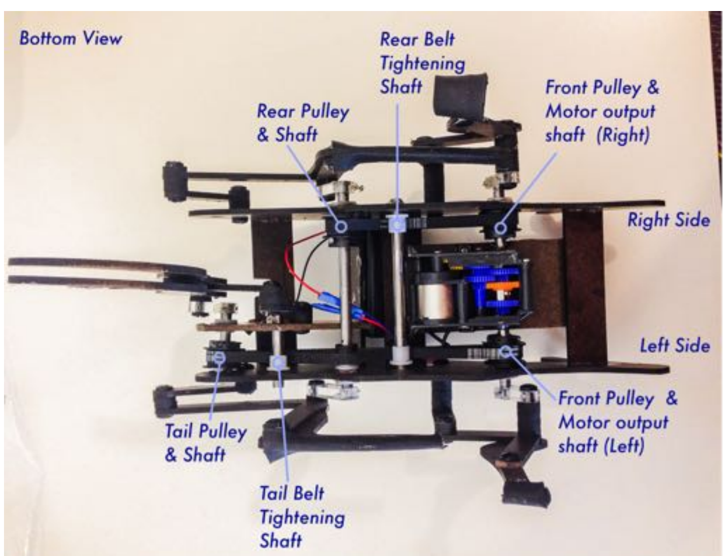


Figure 6: Overhead view of pulleys, belts, and axles that transfer power from the motor to the legs and tail.

Figure 7: Different axles with different hole locations for the front legs (short, to attach to the motor output – top), tail (top), and rear legs (first and second versions, bottom).

All the shafts described above spin freely within the frame due to the plastic flanged bearings that we affixed within the holes of the frame.

3.3 Belt-Tightening Axles and Idler Pulleys

To prevent belt slippage, we inserted two axles in the frame that would improve the wrap-angle and tension of the timing belts on the pulleys. One of these axles, the rear belt-tightening axle, was placed between the front and rear pulleys such that it pressed down on the timing belt running along these two pulleys while also increasing tension in the fore-to-tail timing belt. The second, shorter axle ran between tail-stabilizing frame and the left kangaroo side frame to further tighten the fore-to-tail timing belt and improve the pulley wrap angle.

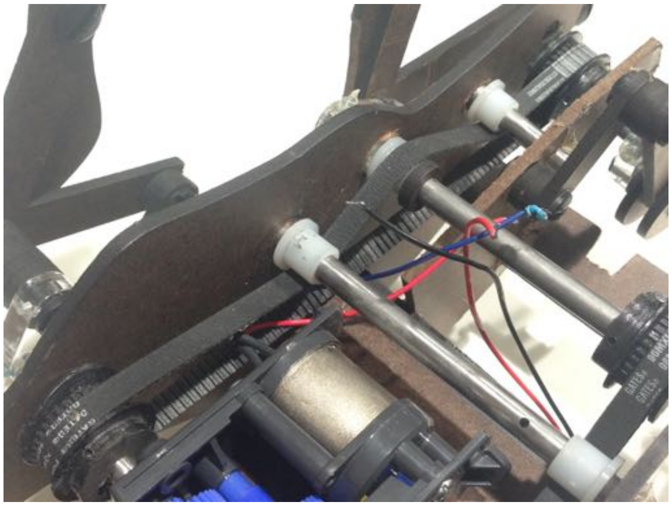
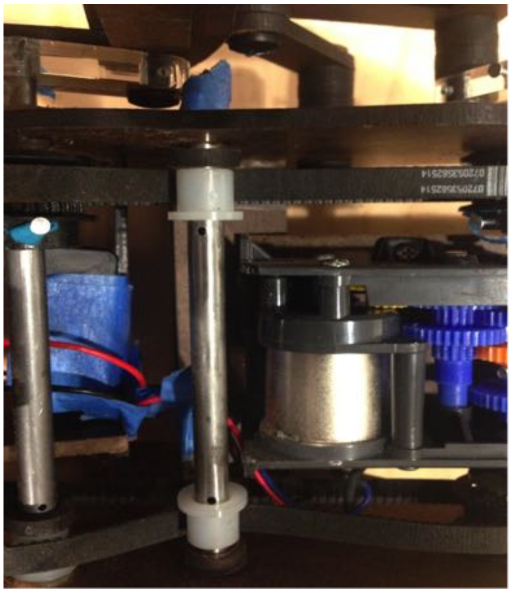
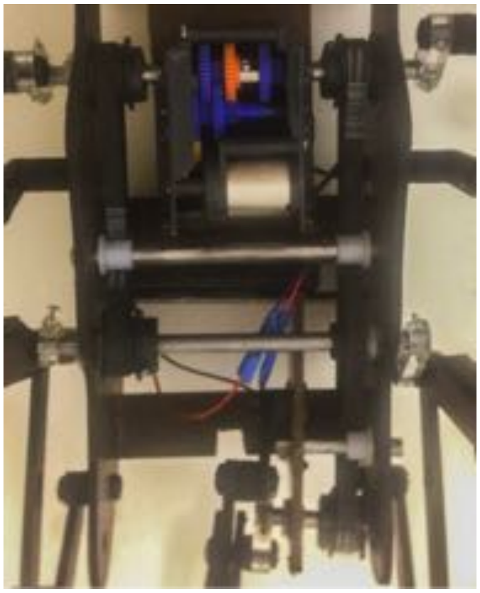


Figure 8: Many bearings were used to serve as idler pulleys to improve the wrap angle and increase the tension of the belt. Some bearings were even placed on the limb axles, again, to increase belt tension

Similarly to how the flanged bearings reduced friction between the shafts powering the cranks of the limbs, additional bearings also mitigated friction between the timing belts and the belt-tightening axles. In this case, the timing belts ran along bearings, which freely rotated about the fixed tightening axles. The bearings served the same function as idler pulleys in this instance.



(a) Both axles with idlers to tighten timing belts.



(b) Back Leg.

Figure 9: Idlers.

3.4 Motor, Transmission and Power Source

We used a Tamiya 6-speed H.E. gearbox to drive five 4-bar linkages. At our nominal voltage of 3V, this motor's initial no-load RPM was 9400. To achieve our desired speed range of 10cm/s - 15cm/s, and approximating our kangaroo to travel roughly two thirds of its body length (18cm) per cycle, we estimated that our crawler would need a linkage cycle speed of around 40 cycles per minute; this relates to a motor output angular velocity of roughly 40RPM. Of the six transmission options, we chose an internal transmission ratio of 196.7:1 as it resulted in the most reasonable output angular speed; the no-load output was 47.8RPM. After further analysis we found this ratio to meet the predicted power and torque requirements (Please see Appendix A).

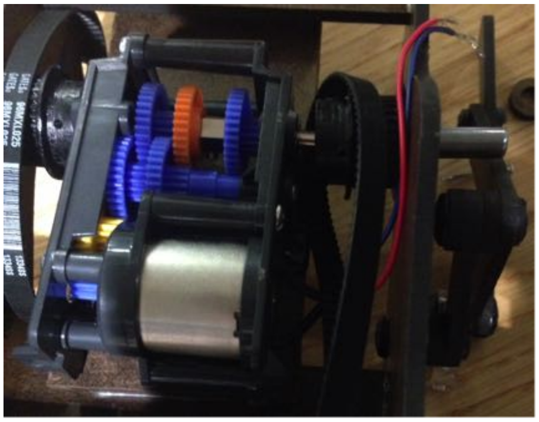


Figure 10: A closeup of the motor and transmission.

The motor was screwed into the underside of the motor attachment frame. We lubricated the transmission gears with oil to reduce friction and improve transmission efficiency. To provide the desired voltage of 3V we used a twin AA battery pack that linked two 1.5V AA batteries in series. The battery pack was housed in the middle of the kangaroo with its base hot glued to the rear crossbar such that the switch was accessible and the pack could be easily slid out of the frame to exchange batteries if necessary.

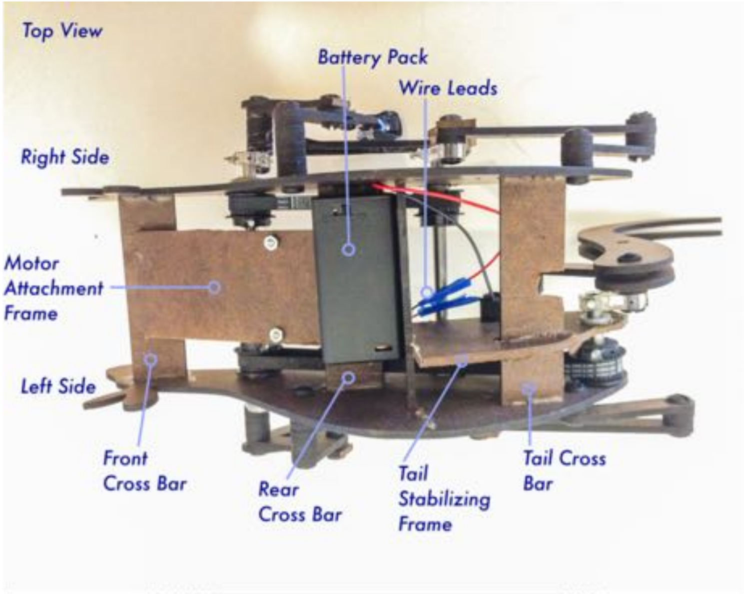


Figure 11: Top view.

3.5 Booties

To provide greater friction between the fore and hind feet and the ground, we added rubber "booties" constructed of bicycle tire strips. We attached initial boot prototypes with blue tape for proof of concept. For the final design we hot glued cut-to-length tire strips to the bottom of the limbs. These booties allowed the kangaroo to propel itself forward without slippage between the kangaroo's feet and the floor. We also incorporated foam to make the booties wider than the original 0.125" duron feet, which reduced the chance that the feet might become wedged in any cracks in the walking surface at Meyer Green. To correct for the initial tendency of the kangaroo to turn left, we slightly tilted our kangaroo's right side upwards by adding extra foam and making the right front boot a little thicker than the others. We also experimented with other potential modifications to correct the steering (Please see Appendix D).

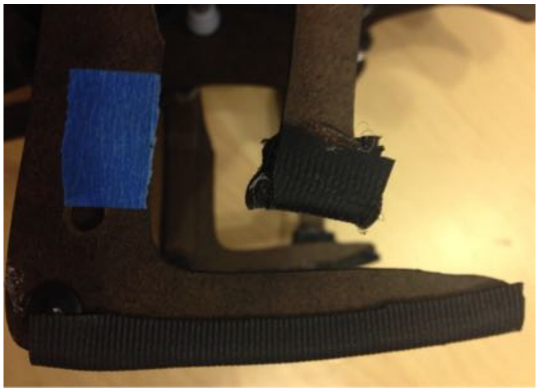


Figure 12: Booties on the back and front feet.

3.6 Rudder

In another attempt to correct the kangaroo's inclination to move to the right, we added a rudder to the tail that helped steer the kangaroo left. As the kangaroo moved forward, the rudder pushed the rear of the kangaroo right, causing the front of the kangaroo to pivot left.

(a) The kangaroo outfitted with an adjustment rudder attached to its tail.

(b) A closeup view of the rudder.

Figure 13: Rudder.

3.7 Identifying Biomimetic Linkage Curves

To find curves that our kangaroo's limbs should follow we further analyzed the previously cited video of the kangaroo's pentapedal gait. We aligned screen shots of the video-recorded kangaroo employing pentapedal motion so that its body maintained roughly the same position while the limbs moved relative to the body (O'Connor). In each screen shot frame we marked dots on the feet, arms, and tail. By tracing these dots that indicated the kangaroo limb positions, we drew highly informed curves of kangaroo motion.

Figure 14: Foot location analysis, from stills of a kangaroo movement video.

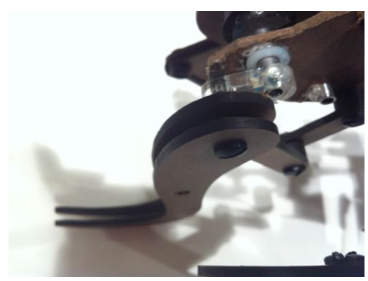
Figure 15: Kangaroo foot curves, consolidated from foot position across all frames in the video. Please note that the tail curve appears shifted up due to three dimensional perspective, but the bottom flat portion of this curve touches the same ground plane as the fore and hind limbs.

We determined that our pentapedal kangaroo should have forelimbs (red), hind limbs (green), and a tail (orange) that followed the respective curves shown above. Looking at the foot curves derived from the kangaroo video stills, we noticed that the front legs and tail were in contact with the ground for the same approximate distance. In contrast, the back legs contacted the ground for about 1.5 times the distance of the forelimb. Consequently, we decided to make the linkages of our kangaroo's back legs 1.5 times the size of the linkages of the front legs and tail.

3.8 4-Bar Linkages

(a) Front linkage.

(b) Back linkage.



(c) Tail linkage.

Figure 16: Closeups of linkages.

To achieve pentapedal locomotion we decided that two pairs of linkages would form the motion for the fore and hind limbs while another independent linkage would establish the motion of the tail. The rockers, couplers, and limbs were made of duron. We fashioned the cranks from 0.25" acrylic, which enabled us to drill holes through them in order to attach them to the crank shafts using pins (Figure 17). Plastic binding posts bound the linkages and served as linkage joints. To prevent the linkages and binding posts from rubbing against each other, we spaced them apart with duron washers. Since we had only one tail linkage, we glued two tail pieces to the coupler to increase the stability of the kangaroo's tail.

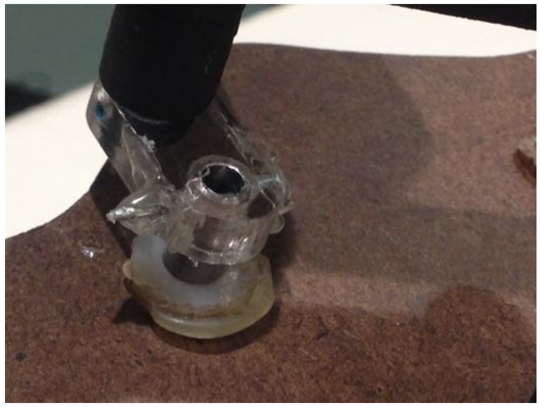


Figure 17: We used thicker acrylic instead of duron for the crank linkages, as we could easily drill holes and use pins to fix the linkages to their corresponding axles and shafts

3.9 Identifying Biomimetic Limb Synchronization

To yield a truly biomimetic pentapedal gait, our kangaroo's limbs not only needed linkage curves that resembled those of a live kangaroo, but also had to move its limbs along these curves in a coordinated manner the movement pattern of a kangaroo. We studied video and force analysis of kangaroo movement to understand the details of limb phasing and found that the tail, fore and hind limb linkages all move synchronously at different points along their assigned curves. In the video, one cycle took roughly 1.5 seconds, or 40 cycles per minute.

For our operating kangaroo we measured a cycle duration by recording the time necessary for the assembly to complete 10 cycles. The cycle duration was thus calculated as (time of 10 cycles)/10 cycles = time/cycle. The velocity was calculated by measuring the time it took for the kangaroo to traverse 1 meter.

As such, we found that the cycle duration for the unloaded kangaroo was 1.1s and loaded kangaroo 1.4s, which was fairly similar to our predicted cycle duration. After measuring the distance taken for the walker to traverse 1m with both low charge (2.95V) and high charge (3.02V) batteries, we found the walker velocities to be 11.2 cm/s and 12.3 cm/s, respectively.

3.10 Our Linkage Curve Synchronization

Throughout our design process, we were able to compare our observed limb phasing to the proper phasing indicated by O'Connor et al. We determined that the fore and hind limbs as well as the tail should start at different points in their respective curves. While the normal and shear force curves on the fore and hind limbs were different, we planned to match these forces by adjusting the relative position, length, and orientation of the fore and hind limbs as well as the overall weight distribution within the kangaroo. The phasing of our kangaroo's limbs could be changed by loosening the appropriate timing belt, shifting the pulley, and retightening the timing belt. This process was necessary in order to determine the ideal position of the limbs relative to each other.

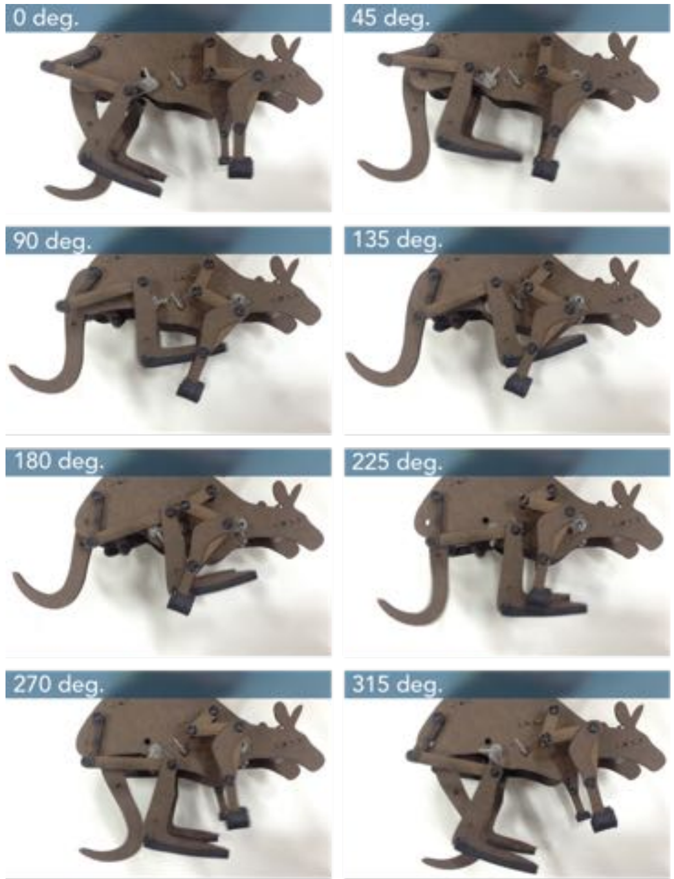


Figure 18: Kangaroo at different angles of the crank.

For the following passage, please refer to the accompanying figure (Figure 18)for reference.

Our kangaroo's cycle began with the kangaroo planting its forelimbs on the ground while its hind limbs supported its weight (0 deg.). Once the forelimbs were securely on the ground, the tail contacted the ground between the back limbs, lifting the back limbs up and forward (45-135 deg.); this action shifted the center of mass of the entire kangaroo forward. The back limbs were planted on the ground next to the front limbs (180-225 deg.), lifting the front limbs off the ground. In the next phase, the relatively low friction of the tail allowed it to be pulled forward along the ground while still supporting the kangaroo's weight together with the hind limbs (270 deg.) The kangaroo's center of mass then moved in front of the contact point of the hind limbs (315 deg.), which caused the kangaroo to tip forward, lifting the tail off the ground and falling onto its fully extended front legs (0 deg.).

While this motion cycle was similar to the motion cycle described in the paper by O'Connor et al., there were a few minute differences. A real kangaroo has a flexible tail that changes its curvature during the motion cycle in order to extend and contract its length. Since our tail was a rigid body, it needed to slide along the floor in order to accommodate a similar motion. Furthermore, real kangaroos extend their bodies and reach further forward with its front legs, moving further per cycle than our kangaroo with a rigid body construction. Even so, the relationship between the forces acting on the kangaroo and the location of the center of mass were very similar.

In earlier prototypes, matching legs were out of phase from each other, which caused the kangaroo's motions to become unstable, since it created forces on the kangaroo perpendicular to its line of direction. As a result, the kangaroo would tend to rotate slightly whenever the unsynchronized legs impacted the ground, causing the kangaroo to walk in a circle instead of a straight line. In order to correct this, we drilled a new hole in the crankshaft and the acrylic crank into which we could insert the pin and realign the limb pairs.

4 Analysis of Performance

Kangaroos use both their hind and forelimbs as well as their tail to provide propulsive and vertical power in a pentapedal gait. Our kangaroo model used an electric motor (Tamiya 6-speed H.E. gear box) to power five separate 4-bar linkages that each act as a limb. A pulley-belt system rotated the shafts connected to the cranks of these four bar linkages. Composed of duron and covered with rubber boots to promote good surface contact, these limbs imitated the pentapedal gait to move the kangaroo forward.

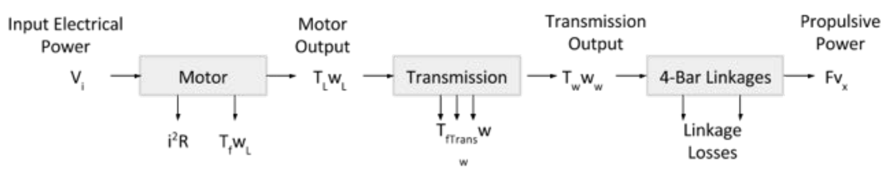


Figure 19: Power transfer diagram.

The diagram above shows the transfer of power from the electric motor, through the transmission, into the 4-bar linkages to yield a propulsive power that moved the kangaroo. To provide this propulsive power we identified 4-bar linkages that produced biomimetic curves that were both effective in walking and mimicking a kangaroo's pentapedal motion.

4.1 Our Linkage Curves

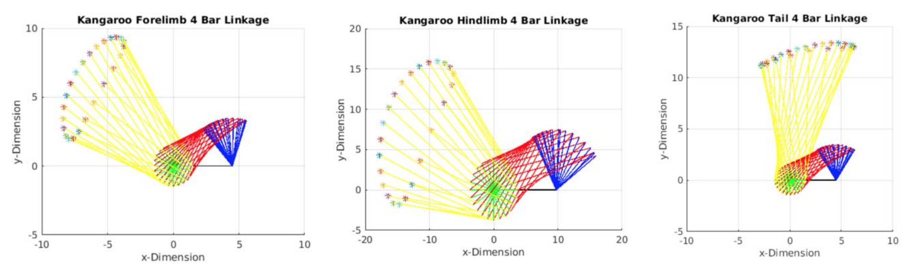
Having identified kangaroo limb curves and their relative position on these curves at different points in the gait cycle, we explored 4-bar linkage curves that closely matched these ideal curves. After identifying a 4-bar linkage design that produced a suitable curve, we modified its coupler point and relative size to better match the desired tail, hindlimb, and forelimb curves. (Please see Appendix C.1 for more detail on our design process for determining an initial suitable 4-bar linkage and associated coupler curve). We chose the linkage curves below because they have a relatively slow and flat area on the ground, and a fast motion pulling back in the air.

Our kangaroo's overall length was 26 cm, its height was 17 cm, and our desired speed was 10-15 cm/s. Based on the dimensions of our kangaroo, and our desired speed, we chose the following lengths for our 4-bar linkages:

	Limb Length	Crank	Rocker	Frame	Coupler
Front Leg	9 cm	1.5 cm	3.5 cm	4.5 cm	4.5 cm
Back Leg	9 cm	2.5 cm	5 cm	6.5 cm	8.5 cm
Tail	13 cm	1.5 cm	3.5 cm	4.5 cm	5.5cm

Table 1: Linkage lengths for the front legs, back legs and tail of the kangaroo.

For the hind limb curve, changes to the relative coupler point led to a different curve from the one we found for the forelimb. Furthermore, looking at the foot curves derived from the kangaroo video stills, we noticed that while the front legs and tail were in contact with the ground for approximately the same distance. In contrast, the back legs contacted the ground for about 1.5 times the length of distance. Consequently, we decided to make the linkages of our kangaroo's back legs 1.5 times the size of the linkages of the front legs and tail. Taking this proportionality information, the dimensions of our kangaroo, and our desired speed into consideration, we chose the above lengths for our back legs' 4-bar linkages. The linkages of the tail and the front legs were identical in dimension because, as we observed from the kangaroo's curves, they covered the same distance. However, we placed tail's coupler point further away from the coupler than we did for the front leg's coupler point. This gave the tail a larger coupler curve that also more closely mimicked that of a kangaroo tail. We confirmed the fore and hind limb linkage curves using Working Model (Appendix C.2).



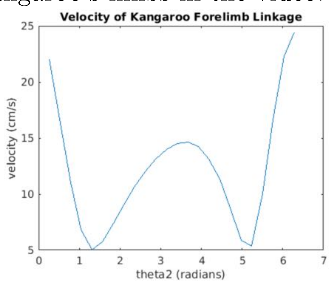
(a) Front leg. (b) Back leg. (c) Tail.

Figure 20: Linkage paths in Matlab.

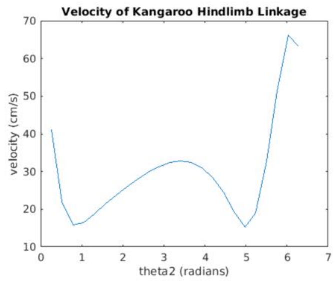
4.2 Coupler Curve Velocities

Assuming the angular velocity of the crank shafts to be constant at the 36rpm predicted by the motor characterization analysis, we also generated velocities of our linkages at the coupler points throughout their respective curves using the half angle equation (Please see Appendix E).

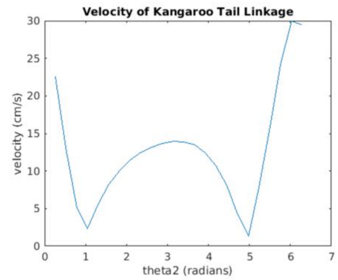
The following figures show the velocities of the couplers throughout the cycle. Since our 4-bar linkage ratios were similar for the front legs, back legs, and tail, the velocity profiles are also similar. The hind limbs are slightly larger, and the tail slightly slower than the front legs due to the differences in length of the 4-bar linkages. All coupler points experience maximum velocity at the end of their cycle, when they are in the air being pulled forward. They were slowest at each end of their coupler curves, when they were just beginning contact or leaving contact with the ground. This was ideal because it closely mimicked the motions of the real kangaroo's limbs in the video.



(a) Front leg.



(b) Back leg.



(c) Tail.

Figure 21: Velocity graphs in Matlab.

4.3 Motor Characterization

We characterized our motor to establish the normal angular velocity of our motor and generate the curves shown above. This characterization also enabled us to determine where on the torque, power and efficiency curves our motor operated during general and high stress parts of the cycle and compares these values to those predicted by the heuristic and force plate analyses.

In this analysis we made the following two assumptions:

1). We assumed the values presented in the Tamiya 6 Speed High Efficiency Motor and Mabuchi RE-260RA data shates were characteristic of our motor.

2). We assumed that the resistance of the batteries remained roughly constant during use.

We used a Tamiya Motor and Gearbox set with a Mabuchi RE-260RA hobby motor in our kangaroo walker. Based on the no-load speed and stall current given in the datasheet, we were able to estimate the internal resistance and motor constant for our Mabuchi motor. For this process we used the following equation:

$$V = IR + k\omega \tag{1}$$

Where omega is the angular velocity, k is the motor constant, V is the voltage, and I is the current.

Using the nominal 3V voltage in conjunction with the motor datasheet as well as the stall current, we found our internal resistance as follows:

$V = I_{stall}R + k\cdot(0) \Rightarrow R = \frac{V}{I_{stall}} \Rightarrow R = 1.1\Omega$

Using this resistance value, we then used the no-load measurements from the datasheet to determine the motor constant k of our Mabuchi motor.

$k = \frac{V - I_{nl}R}{\omega} \Rightarrow k = 2.9\cdot 10^{-3} Nm/A$

Using working model we predicted the distance traveled per cycle to be 18.75cm (Appendix A).

$D_{cycle} = 18.75cm = 0.1875m$
$V_{desired} = 12.5cm/s = 0.125m/s$
$T_{cycle} = \frac{D_{cycle}}{V_{desired}} = \frac{0.1875m}{0.125m/s} = 1.50s$
$Angularvelocity = \frac{1}{T_{cycle}} = 0.667rotations/s = 4.1888rad/s = 40rpm$

With a no-load RPM of 9400 and a gearbox transmission ratio of 196.7:1, our motor and transmission system yielded a no-load output of 47.8RPM, or 287 deg/sec. This system met the predicted power and torque requirements (see below), and emerged as the most suitable transmission system to attain 40RPM for our linkage cycle.

Angular velocity at the transmission output (ω_w) can be calculated based on the transmission ratio and the angular velocity of the motor (ω_L) as follows:

$\omega_L = 9400rpm$
$\omega_w = \frac{\omega_L}{transmissionratio} = \frac{9400rpm}{196.7} = 47.78rpm$

47.78 rpm was much closer to the desired angular velocity of 40rpm than the other angular velocities yielded by different transmission ratios.

The closest alternative transmission ratio was 505.9. However that yielded an angular velocity of 18.58 rpm, which was not as close to the target of 40rpm as 47.78 rpm.

$\omega_w = \frac{\omega_L}{transmissionratio} = \frac{9400rpm}{505.9} = 18.58rpm$

Furthermore, since these angular velocities were calculated given no-load conditions, we know that the operational angular velocity would be somewhat lower than 47.78 rpm and even closer to the desired 40rpm than our no-load analysis suggested.

Taking this gearbox transmission into consideration, we are able to determine output torque and power from our motor and gearbox system.

Where P is the power, T_l is the load torque and T_f is the torque of friction.

We measured the voltage supplied to the motor to be 2.6V on test day. Using a power supply to run our kangaroo at an input voltage of 2.6V, we measured our operating current to oscillate between 0.50A and 1.05A. From these current measurements, we determined the operational power, torque, and efficiency values for our motor at different stages in the kangaroo's walking cycle. The point at which the kangaroo draws 1.05A represented the point in the cycle when the kangaroo pushes off its hind legs. This was the point of greatest stress in the cycle, and required 480mNm of torque and 1.32W of power.

$$T_l = kI - T_f = 2.9 \cdot 10^{-3} \frac{Nm}{A} \cdot 1.05A = 480mNm \quad (2)$$

From Equation (1):

$$\omega = \frac{V - IR}{k} = \frac{2.6V - 1.05A \cdot 1.1\Omega}{2.9 \cdot 10^{-3}} = 2.717rad/s = 25.95rpm \quad (3)$$

Therefore:

$$P_{out} = T_l \cdot \omega = 480mNm \cdot 2.717rad/s = 1.32W \tag{4}$$

From our motor characterization at an input of 2.6V, we calculated our maximum available power output of our motor to be 1.42 W, and our maximum available torque of to be 1.26Nm. The maximum available figures were indeed above the required power and torque at the kangaroos point of greatest stress.

(Please see Matlab Motor Characterization source code in Appendix D4 for detailed calculations of maximum available and required motor torque and power for our kangaroo).

Below are motor curves that describe torque, power, and efficiency with respect to angular velocity for the Mabuchi RE-260RA which comes with the Tamiya 6 speed motor and gearbox kit. Motor efficiency curves were generated from the following equations:

$$P_{in} = IV \tag{5}$$

$$Efficiency = \frac{P_{out}}{P_{in}} \tag{6}$$

In the figures below, the black circles indicate at which point the motor operates during the majority of the cycle as calculated using the average exerted torque. The red circles indicate at which point the motor operates during the most challenging portions of the cycle. The blue stars indicate at which point the motor operates during the most challenging portions of the cycle as calculated as calculated using the force plate values. The magenta stars indicate predicted motor operation at the challenge point using the force heuristic analysis. Calculations and analysis for the predicted torque and power requirements using force heuristic assumptions can be found in Appendix D.2.

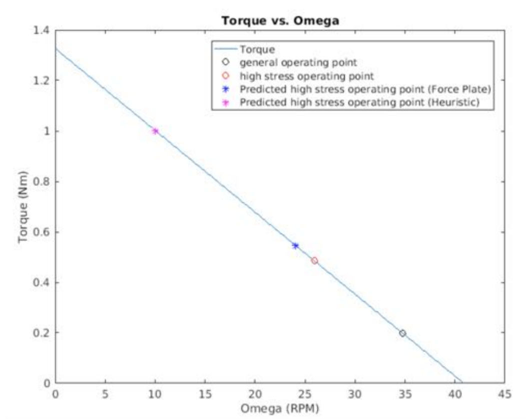
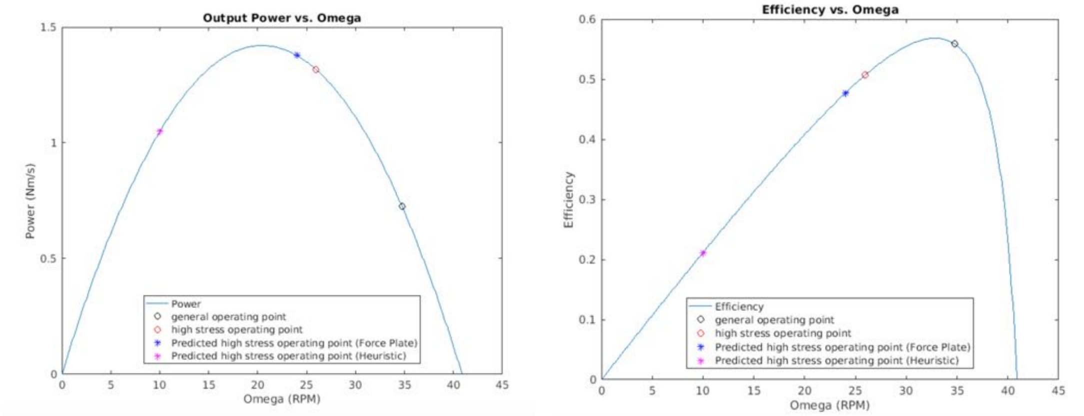


Figure 22: Motor Efficiency versus Omega and operating point

As can be seen from these graphs, at the general operating point our motor operated near peak efficiency while at the high stress operating point it operated near peak power output. Note how our high stress operating points from our prior force heurisitic analysis and force plate analysis both anticpicipated greater loads than was actually found (Please see Appendix A). Thus, they were shifted left on these curves. Given the worst-case assumptions present in the predictive analyses, this result is not surprising. However, the force-plate predicted a high stress operating point that proved fairly accurate.



(a) Motor Power versus Omega and operating point.

(b) Motor Efficiency versus Omega and operating point.

Figure 23: Motor Efficiency versus Omega and operating point.

4.4 Force Plate Analysis

Shear Force During impact with the ground, the maximum forelimb shear force was about -1.25 N, and with an average that was about -0.5 N. These negative values meant that the forelimbs acted as brakes against the kangaroo's forward motion throughout the cycle.

As the hind legs touched the ground they exerted a shear force that began as roughly 0.5 N and slowly transitioned to -0.25 N. These forces indicated that the hind legs were pushing the kangaroo forward in the beginning of the cycle until the kangaroo began to fall onto its fore legs, at which point the hind legs held the kangaroo back. Finally, the maximum tail shear force was about 0.35 N, and the average was around 0.1 N. These positive values meant that the tail was pushing the kangaroo forward.

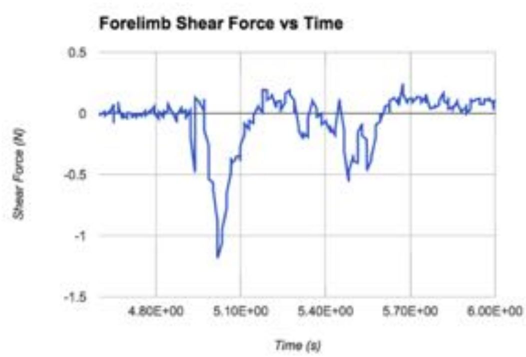
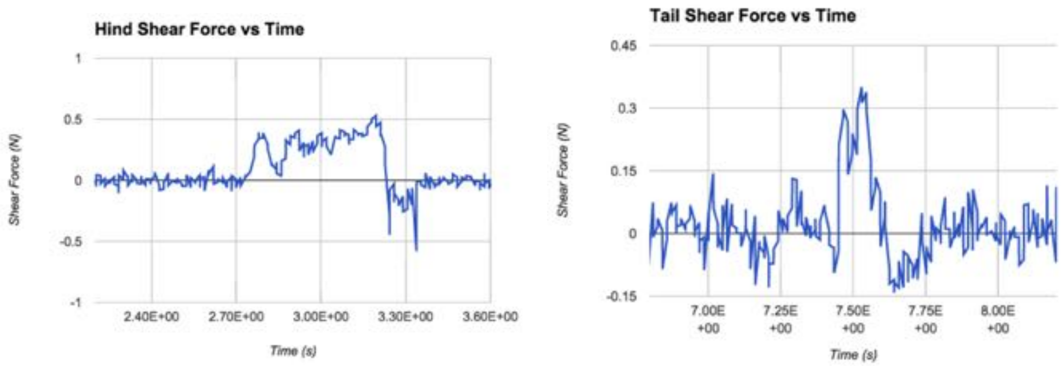


Figure 24: Force plate data of shear forces on front legs in the x-direction during impact.

As described by O'Connor et al, in order to mimic the real kangaroo, the tail of our kangaroo should only push forward, which would be reflected in a positive shear force in the x-direction. Our walker successfully imitated this aspect. However, the force was only about 0.35 N, which was relatively low in proportion to the other limbs. The force should be approximately at least equal, but opposite to, the shear force of the forelimbs, which were braking, and greater than the hind limbs that would propel and brake the kangaroo. However, the front legs' shear force of -0.5 N was larger than that of the tail. The values of the front leg shear forces are initially slightly too large, perhaps because our frontlimbs lacked the shock absorbers of real kangaroo tendons. However, these shear force values, for all limbs, were reasonable.



(a) Back leg. (b) Tail.

Figure 25: Force plate data of shear forces in the x-direction during impact.

Normal Force During impact with the ground, the maximum forelimb normal force was about -5 N, and the average was around -2.5 N. This meant that the forelimbs were pushing down on the ground. The maximum hind leg normal force was around -3.5 N, and the average was around -1.5 N. This meant that the hind legs were pushing down on the ground. The maximum tail normal force was around -1 N, and the average was around -0.75 N, which demonstrated that the tail was pushing down on the ground.

Once again, the normal force ratios of the different limbs are reasonably proportional to those found by O'Connor et al. The tail should have pushed downward with roughly equal the force of the forelimbs, which was about -2.5N, and half the force of the hind limbs, which was actually -1.5N. This meant that the forelimb normal forces were proportionally too large, and the hind limb normal forces were proportionally too small. Perhaps we should have changed the mass distribution such that the tail and hind limbs took more of the weight. However, our walker still performed admirably in this regard.

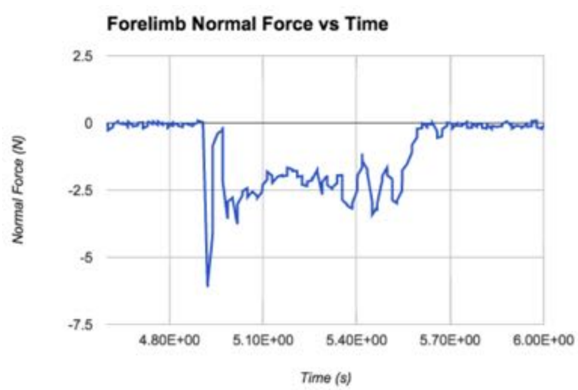
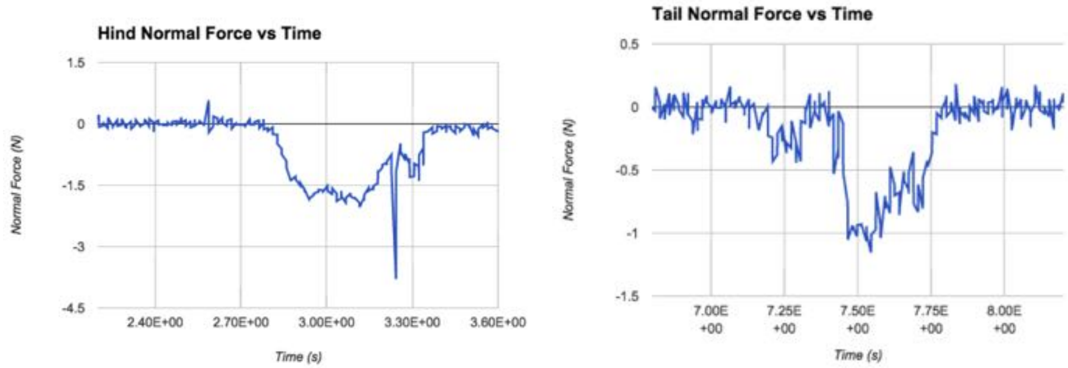


Figure 26: Force plate data of normal forces on front legs during impact.



(a) Back leg. (b) Tail.

Figure 27: Force plate data of normal forces during impact.

5 Redesign

While our kangaroo walker satisfied our initial design requirements, some components could be improved. Firstly, the steering of our kangaroo was somewhat unreliable, turning slightly left or right. Before the Down-Under exhibit opens to the public, we would first improve the kangaroo's ability to consistently walk in a straight path. To achieve a straighter path, we could experiment with shifting the weight balancing in both the fore-aft and left-right directions. We would also explore methods of self-correcting steering. Additionally, we would more precisely synchronize the two front legs and the two back legs by precisely re-drilling shafts and cranks such that all the holes and therefore limb positions are appropriately aligned. We could thus fine-tune their relative positions and perfect the phasing between each linkage. Perhaps the most crucial change to achieve this straight-steering objective would be realignment of the two sides of the frame to make the kangaroo more symmetrical, which would likely make its steering more consistent.

To make our kangaroo limbs' force and power distributions more natural, we would possibly move our battery pack or add additional weights to better mimic the body weight distribution of a real kangaroo. We could also adjust the gait cycling, and coupler points, to recreate more realistic limb forces and power ratios. To prevent uncontrolled radial rotation, we would carefully tighten the pin connections between motor output shafts, rotary shafts and cranks. This would minimize the play between the forearm shaft and the motor shaft and ensure that the arms, and thus the legs and tail, move responsively to the driving of the motor. We would also consider actuated feet and flexible limbs that could store and release kinetic energy and improve our walker's force and power distributions. Finally, to achieve more consistent, robust performance, we would conduct crash tests against impact and rough handling on different material surfaces and on slightly inclined surfaces.

6 Conclusions

All in all, our kangaroo walker performed quite well. Our autonomous kangaroo walker travelled smoothly over the paved stone area of Meyer Circle in wet and windy conditions and successfully reached the far edge of the patio. It achieved a speed of 11.2 cm/s, which lay within the required speed range of 10-15 cm/s. Also, its frame shape, limb placement, limb curves, and limb synchronization closely resembled those of a real kangaroo. Furthermore, the force and power generation sequence of our kangaroo walker limbs in the vertical and fore-aft directions were also biomimetic. As such, our kangaroo both looked and operated much like a real kangaroo in achieving a pentapedal locomotion.

On performance day, although its overall velocity was still within the accepted range, our kangaroo moved slightly more slowly than expected on the hindlimb drive phase due to low-charge batteries. We corrected this problem afterwards by exchanging the old batteries for new ones, and the kangaroo was then able to resume its expected speed. Our kangaroo temporarily turned slightly left but it soon resumed a straight course without adjustment. The uneven nature of Meyer Circle and asymmetries in the two sides of the frame design may have contributed to this steering issue. To most improve our kangaroo, we could adjust the two sides of the frame to make the walker more symmetrical and hopefully prevent it from turning in similar conditions. We could also add compliance to the hind and fore limbs to produce a more even gait, more closely mimicking that a living kangaroo.

7 Appendices

A Predicting Max F: Torque and Power requirements

A.1 Heuristic Predictive Analysis

In addition to showing that the 4-bar linkages produced ideal position and velocity curves, we conducted further power and torque analysis to predict the viability of these linkages. In the following analysis we approximated the anticipated power and torque requirements and compared that to the capability of our motor.

Finding Predicted Maximum Force, Power and Torque Requirements and Capabilities

Assumptions:
1) We assumed the average force on the limbs to be equal to the weight of the kangaroo.

2) We assumed that the total acceleration maximum equals 2g given the dynamic force balance heuristic (Affine Transformations Lecture Handout).

3) To ensure that our analysis would not overestimate the ability of our kangaroo, we also assumed the worst-case possibility that the maximum force, lever arm, and velocity values all occurred at this same point in the cycle with the maximum force being solely concentrated on the hind limb, which had the biggest lever arm of the limbs. Although false, this worst-case assumption ensured that our kangaroo would be able to meet its requirements in normal conditions.

4) We assumed that the angular velocity of the crank was constant in producing the velocity curves above.

With the calculated power and torque plots, we used these assumptions to compare our predicted required forces to the capabilities of our kangaroo. We assumed the average force on the limbs to be equal to the weight of the kangaroo (Affine Transformations handout). Based on the materials we planned to use, we predicted the kangaroo to weigh half a kilogram.

$F = ma$
$\Rightarrow F_{ave} = 0.5kg \cdot 9.8m/s^2$
$R_{ave} = centroidofsemicircleaway = \frac{4r}{3pi} = \frac{4 \cdot 8}{3\pi} = 3.395cm$

$T_{ave} = F_{ave} \cdot r_{ave}$
$T_{ave} = 4.9N \cdot 0.03395m = 0.166355Nm$

Given this average torque value and the omega vs torque graph shown above, we expected the motor to run at 36rpm, which is near the peak of the efficiency curve. The free body diagram below helps illustrate the loading on the kangaroo.

Using the dynamic force balance heuristic that the total acceleration maximum equals 2g (Appendix C2), we calculated the max force experienced by pair of limbs to equal 9.8N.

$F = ma$
$\Rightarrow F_{tot} = 0.5kg \cdot 2 \cdot 9.8m/s^2 = 9.8N$

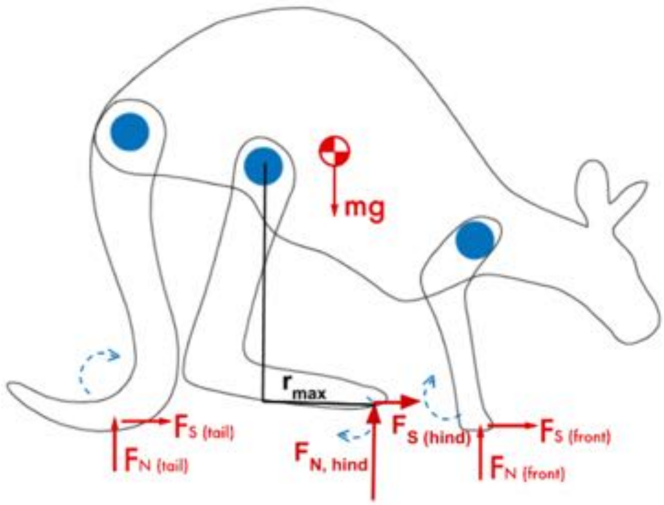


Figure 28: A free body diagram of the overall system. Forces may be negative in different parts of the cycle for different limbs. The current position demonstrates forces acting on the kangaroo when the moment arm on the hind limb is the greatest.

According to our Matlab and working model velocity curves, the peak velocity for when the limbs were on the ground was 31.0 cm/s, or 0.310 m/s. Therefore, the peak predicted required power was 3.316W.

$P_{req} = FV$

$\Rightarrow P_{req} = (9.8N \cdot 0.310m/s) = 3.04W$

Our max power output capability was 1.42W. At $\omega = 36$rpm, the motor power is roughly 0.6W. Thus, at this point the velocity would have to decrease in order to diminish the power demands as well.

However, further analysis did show that even though it would have to slow, the motor would not stall at this and other challenging points. We compared the maximum torque capability of the motor with the maximum required torque at these points.

$T_{max,req} = F_{max} \cdot r_{max}$

Considering the position of the 4-bar linkages, we found that the maximum effective lever arm occurs on the hind limbs as the forelimbs rose off the ground. At this point the effective lever arm distance was equal to 8cm. To ensure that our analysis would not overestimate the ability of our kangaroo, we also assumed the worst-case possibility that the maximum force, lever arm, and velocity values all occurred at this same point in the cycle, which they did not. Even so, however, our maximum available torque value easily surpassed the worst-case maximum required torque.

$r_{max} = 10cm = 0.10m$

$F_{max,req} = 9.8N$

$\Rightarrow T_{max,req} = 9.8N \cdot 0.10m = 0.980Nm$

As shown by the torque vs omega curve above, our maximum available torque was well above the maximum required torque. We verified this finding with the given motor specification value that motor torque output equalled $0.97 oz \cdot in$, or $6.85 \cdot 10^{-3} Nm$.

Transmission Ratio = 196.7 $T_{max,motor} = 6.85 \cdot 10^{-3} Nm$

$T_{max,cap} = T_{max,motor} \cdot TransmissionRatio$
$\Rightarrow T_{max,cap} = 0.0068497 Nm \cdot 196.7 = 1.26 Nm$
$T_{max,cap} = 1.26 Nm > 0.784 Nm = T_{max,req}$

According to the torque vs omega figure above, our kangaroo should have operated at 10 rpm where the output torque equals the required torque at these more challenging points in the cycle. We thus predicted that our kangaroo should be able to overcome the torque requirements.

With the velocity having dropped from 0.310m/s when it was running at 36 rpm to 0.138m/s at the new angular velocity of 10 rpm, the new power requirement would be 0.135W. As shown by the power vs omega figure above, our available power output at 10 rpm would exactly equal this value.

$v_{new} = v_{old} \cdot \frac{w_{new}}{w_{old}}$
$v_{new} = 0.310 m/s \cdot \frac{10rpm}{36rpm} = 0.086 m/s$
$P_req = 9.8N \cdot 0.086 m/s = 0.843 W.$

Thus, we predicted our kangaroo to be able to match its required torque and power values.

A.2 Force Plate Predictive Analysis

With the limb 4-bar linkages appropriately constructed and synchronized so that our kangaroo walked appropriately, we began comparing our predicted force (and thus power) values with those measured through use of the force plate. Also, the kangaroo's actual mass came to 505g, as opposed to the half kilogram that we predicted.
The force plate measurements were taken by use of 6 capacitive force sensors. Two were aligned to record shear forces while the remaining four recorded normal forces.

Assumptions:
1). Assume worse case scenario that F shear values for the different limbs all occur at the same time. While false this ensures that if the motor can handle this load it can handle any reasonable load that the kangaroo might produce. The force plate didn't allow us to record all the limb forces at the same time it is hard to piece together when they actually occurred in relation to each other. Since the purpose of this portion of the analysis is to show that the motor could handle the loading exerted on it and not to necessarily show the exact loads on it this is acceptable.

2). Assume worse case scenario that the F normal values for the different limbs all occur at the same time for similar reasons as above.

3). Assume worse case scenario the both F normal and F shear values for the different limbs occur at the same time for similar reasons to above.

4). Similarly to one of our previous force heuristic predictive analysis assumptions, to ensure that our analysis would not overestimate the ability of our kangaroo, we also assumed a worst-case possibility. Thus we estimated that the maximum force and lever arm values occurred at this same point in the cycle with the maximum force being solely concentrated on the hind limb, which had the biggest lever arm of the limbs. Although false, this worst-case assumption ensured that our kangaroo would be able to meet its requirements in normal conditions.

Given these assumptions, the $F_{net,shear}$, $F_{net,normal}$, and F_{net} values can be calculated using the equations below.

$F_{net,shear} = F_{fore,shear} + F_{hind,shear} + F_{tail,shear}$
$_{net,normal} = F_{fore,normal} + F_{hind,normal} + F_{tail,normal}$
$F_{net} = (F^2_{net,shear} + F^2_{net,normal})^{0.5}$

From our force graphs, the shear and normal force values on the limbs when in contact with the ground are as follows:

Maximum Values:

$F_{fore,shear} = 0.25N$
$F_{hind,shear} = 0.5N$
$F_{tail,shear} = 0.35N$
$F_{net,shear} = 0.25N + 0.5N + 0.35N = 1.1N$

$F_{fore,normal} = -2.5N$
$F_{hind,normal} = -1.5N$
$F_{tail,normal} = -1N$
$F_{net,normal} = -2.5N - 1.5N - 1N = -5N$

$F_{net} = (1.1N^2 + (-5N)^2)^{0.5} = 5.12N$

$F_{net} = 5.12N$

$P_{req} = FV$
$\Rightarrow P_{req} = 5.12N \cdot 0.310m/s = 1.587W$

At 36rpm, $P_{motor} = 0.6W$

Thus, at this point the velocity would also have to decrease the power demands.

As previously, to find the new angular velocity we looked to the required torque values.
$T_{max,req} = F_{max} \cdot r_{max}$
$r_{max} = 10cm = 0.10m$
$F_{max,req} = 5.12N$
$\Rightarrow T_{max,req} = 5.12N \cdot 0.10m = 0.512Nm$
$T_{max,cap} = 1.26Nm > 0.512Nm = T_{max,req}$

Looking again to the torque vs angular velocity graph, a torque of 0.512 Nm indicated that an angular velocity of 24 rpm would cause the motor to provide a torque equal to this maximum required torque. The new velocity would thus be 0.256 m/s and would require a power of 0.952W.

$v_{new} = v_{old} \cdot \frac{w_{new}}{w_{old}}$
$v_{new} = 0.310 m/s \cdot \frac{24rpm}{40rpm} = 0.186 m/s$
$P_{req} = (5.12N \cdot 0.186 m/s = 0.952W$

At an angular velocity of 24rpm, the power output was approximately 1.3W and exceeded the required power of 0.952W. Thus, this analyis suggested that our kangaroo performed even better than our previous analysis had anticipated and remained close to the peak efficiency value for the majority of its cycle. Thus, our force plate analysis suggested that our kangaroo walker was able to match its required torque and power values.

As shown earlier, however, for the majority of our cycle our kangaroo ran near 36rpm. Thus our kangaroo was predicted to largely operate near its efficiency peak except in the most challenging parts of its cycle, where it would run near its power peak. A model constructed in Working Model corroborated these force and power values and confirmed our findings.

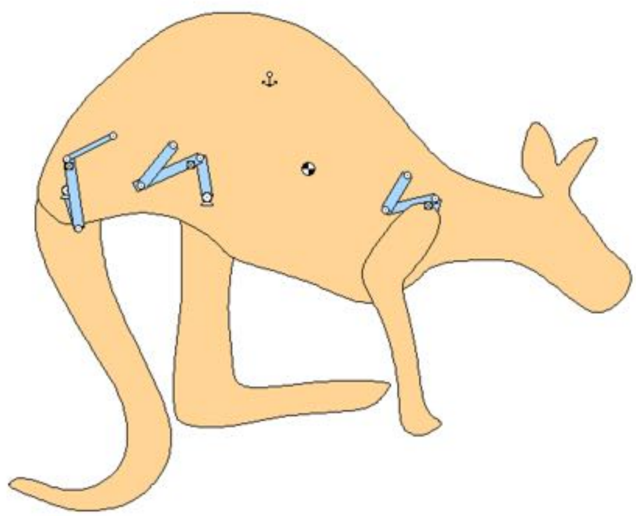


Figure 29: An approximate simulation of the entire kangaroo in wm2d demonstrating the the different 4-bar linkages on one one side the kangaroo. This simulation confirmed the walker's predicted linkage curve velocities and overall speed. It also predicted approximate power requirements.

B First Iteration of Frame

First Iteration Our first kangaroo frame attempted a smiling kangaroo outline, downloaded from the icon library thenounproject.com. This frame enabled initial testing of the location of our linkages and the construction of horizontal supports to connect the kangaroo's left and right sides. This iteration was crucial for prototyping the way we could construct our linkages and body design, but it was quickly discarded, for aesthetic and general biomimetic reasons.

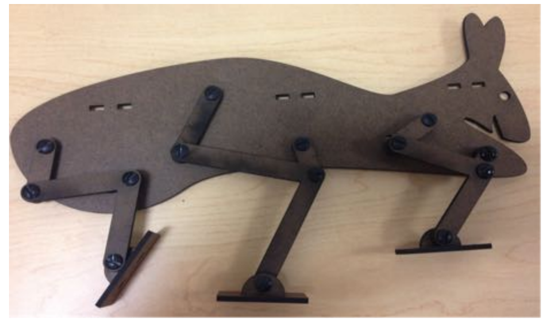


Figure 30: Our first frame, with flat feet.

C Original Linkages

C.1 General Linkages

Here we discuss in greater detail our design process for determining an initial suitable 4-bar linkage and associated coupler curve. Throughout our design process, we were able to compare our observed limb phasing to the proper phasing indicated in this force analysis article. To match the pentapedal gait pattern described above, we determined that the fore and hind limbs as well as the tail should start at different points in their assigned curves. While the vertical and fore-aft force curves on the fore and hind limbs are different, we planned to match these forces by adjusting the relative position, length, and orientation of the fore and hind limbs as well as the overall weight distribution within the kangaroo.

Using this tool: mekanizmalar.com/fourbar.html we simulated various linkage designs to identify a curve that was both natural and effective for walking, with a fast, flat bottom part.

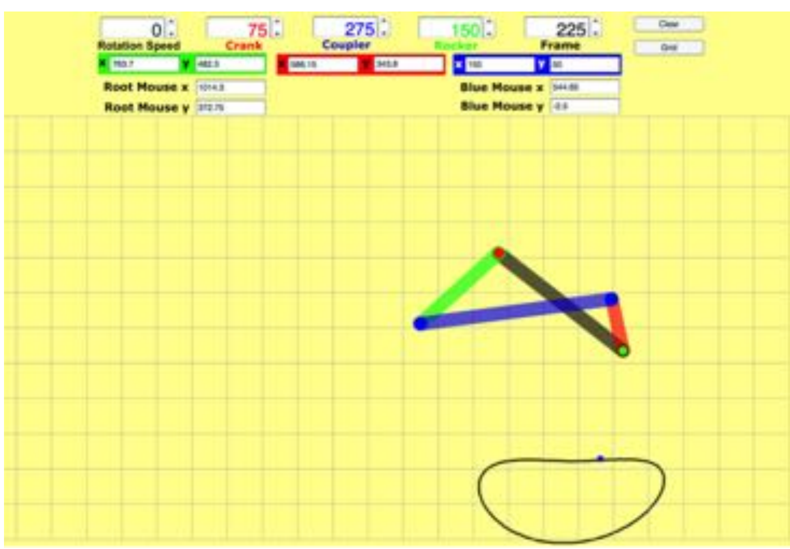


Figure 31: Simulation of potential linkages.

We also drew inspiration for the physical implementation of this curve by studying another successful walker example, an Alligator.

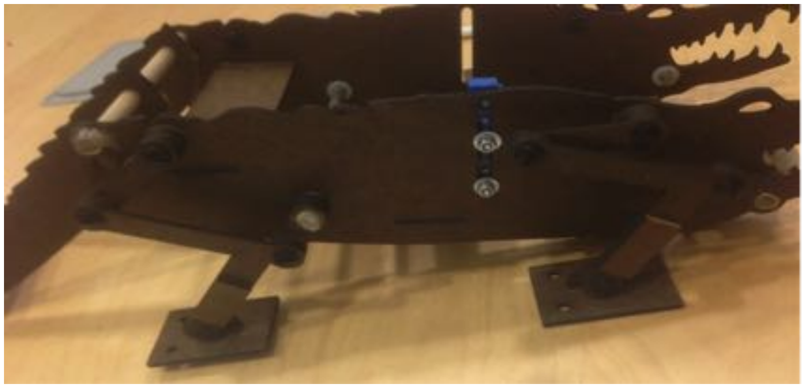


Figure 32: Inspirational alligator design, from a prior year.

After initial explorations, we simulated our 4-bar linkage design in wm2d to understand its output velocity and its required input motor torque, force, and power. Please see the analysis section for a more detailed interpretation of these numbers.

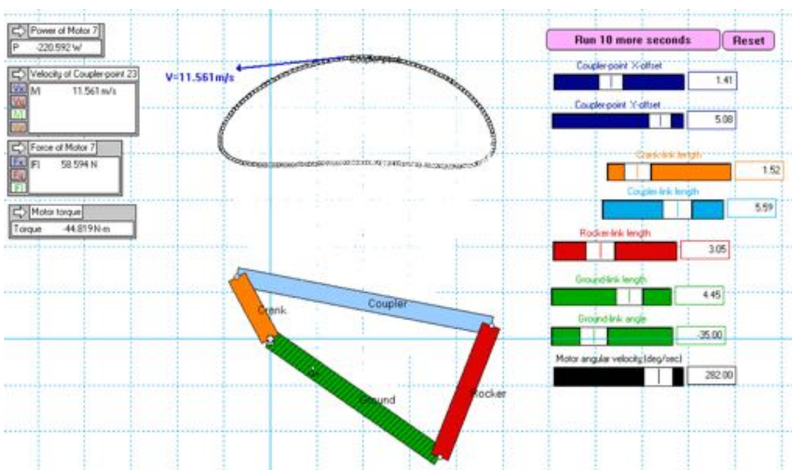


Figure 33: Simulating our linkaged design in wm2d. Please note that the numbers in these simulation screenshots are 100 times larger than in reality since the simulator takes meters, not centimeters, as linkage input lengths.

These estimates ensured that, before we made our first physical prototype, our linkage did not exceed the abilities of our motor and its velocity fell within the desired 10 - 15cm/s.

Here is the linkage, at its highest velocity on the bottom "walking" part of the curve. On the bottom part of the curve, the velocity is nicely consistent between 11.0 and 11.5 cm/s. In the entire curve, the moment of greatest motor torque and power occurs as the linkage decelerates from its fast "leg moving in the air" portion into the "about to step on the ground" portion.

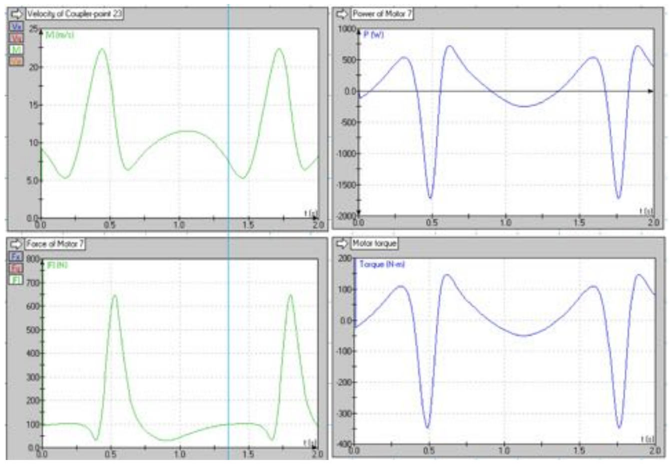


Figure 34: Charts of Force, Torque, Power, and Velocity over time.

After creating this initial working model we used Matlab to confirm the path and velocity graphs with appropriate scaling since the working model software range limits prevented us from putting in our exact values.

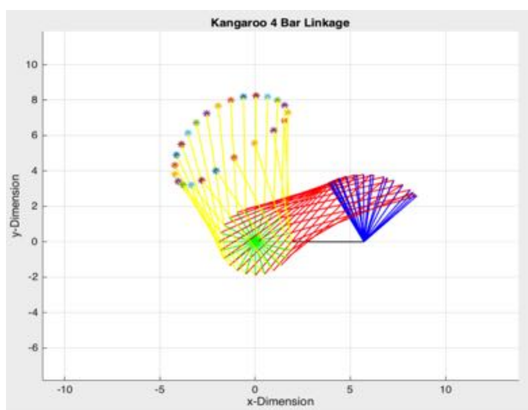


Figure 35: Matlab Linkage Path.

The 4-bar linkage curve established by Working Model is confirmed by the nearly-identical one generated by Matlab.

The velocity curve generated by Matlab also confirms the one established by Working Model.

With the addition of the more realistic forelimbs and hindlimbs of Kangaroo 2 as shown in the Hardware section we adjusted the coupler points and associated gamma c values to generate new curves on Matlab and Working Model.

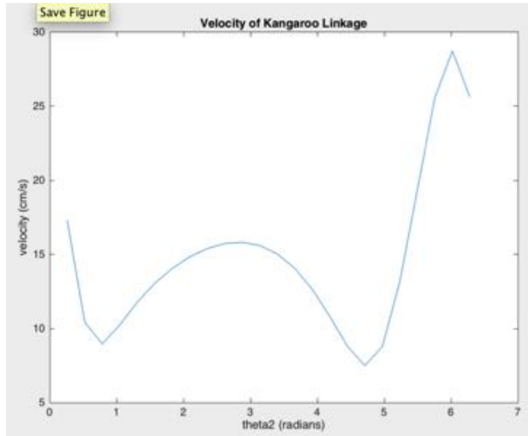


Figure 36: Velocity Graph in Matlab.

C.2 Leg Linkages

We generated Working Model simulations of the front leg and back leg 4-bar linkages. Input range limits prevented us from evaluating the tail 4-bar linkage as well:

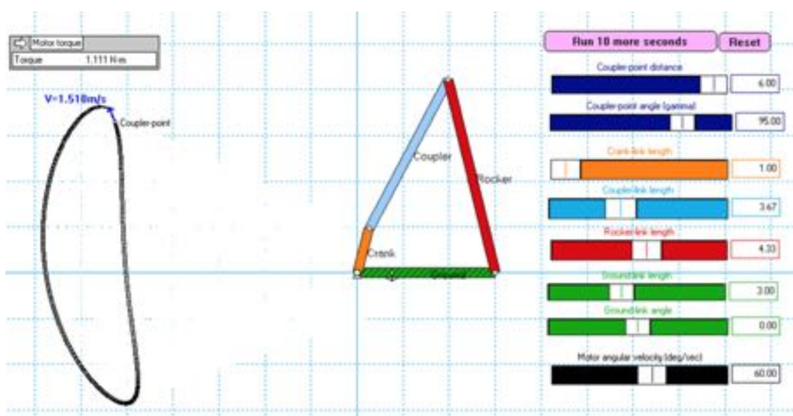


Figure 37: Scaling our linkage for the front leg and tail in wm2d.

Working model helped confirm our predictive analysis of the force-power requirements.

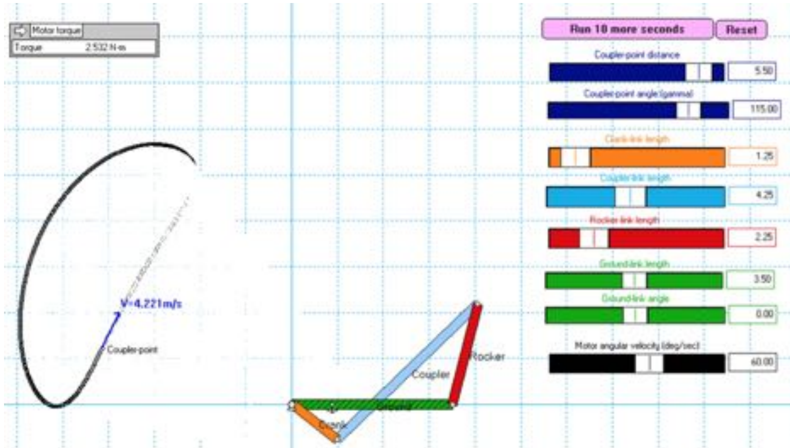


Figure 38: Scaling our linkage for the back leg in wm2d.

D Considered Modifications to Correct Steering

Video analysis suggested that the kangaroo was turning right as it moved forward onto its forelimbs, since it would fall slightly right as the forelimbs began to touch the ground. Thinking that the length of the limbs on the right side might be causing the kangaroo to lean right in this part of the stride, we attempted to lengthen them.

Figure 39: Modification on legs to prevent the kangaroo from turning right.

While this did prevent the kangaroo from leaning to the right as it fell forward, the kangaroo would still turn to the right. Thus, the lean was likely not the dominant factor causing the kangaroo to turn so we removed the hind and forelimb lengtheners and looked for other potential causes.

E Matlab Code

Position and Velocity Curves of Forelimbs, Hindlimbs, and Tail:

E.1 Forelimb Curves

```
% Forelimb

clear all; close all; clc;

% Length of Linkages:
%Given in cm
% (in)*cm conversion
frame = 4.5;
crank = 1.5;
coupler = 5;
rocker = 3.5;
toCouplerPoint = 9;
gammac = pi*(95/180);

%Define range of angles to plot and step size

theta2start = 0;
theta2end = 2*pi;
numsteps = 24;
theta2step = (theta2end-theta2start)/numsteps;
theta2s = [theta2start:theta2step:theta2end];
velocities = zeros(numsteps,1); %empty array

%Guess a reasonable plot area (may need to tweak these)
leftlim = -15;
rightlim = 35;
bottomlim = -15;
toplim = 15;
axis([-10 10 -5 10]);
grid('on')

%The fixed ground link
X1 = 0;
Y1 = 0;
X4 = frame;
Y4 = 0;
line([X4;X1],[Y4;Y1],'Color','k','LineWidth',1);

hold on;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %% Main loop for each crank
angle
```

```
for i=1:length(theta2s)

    cosq2 = cos(theta2s(i));
sinq2 = sin(theta2s(i));

    % Define some substitutions (9.29-9.31)
A = 2*rocker*(frame - crank*cosq2);
B = -2*crank*rocker*sinq2;
C = coupler2̂ - crank2̂ - rocker2̂ - frame2̂ + 2*crank*frame*cosq2;

    %Solve for the roots of half angle equation (9.35)
%If general
u41 = (B + sqrt(A2̂ + B2̂ - C2̂))/(A+C);
q4 = 2*atan(u41);

    %Solve for theta3 (9.37-9.39)
%range = -PI to +PI
cosq3 = (-crank*cosq2 + rocker*cos(q4) + frame)/coupler;
sinq3 = (-crank*sinq2 + rocker*sin(q4))/coupler;
q3 = atan2(sinq3,cosq3); %don’t really need it for plotting

    %Compute locations of joints 2,3
X2 = crank * cosq2;
Y2 = crank * sinq2;
X3 = X2+coupler*cosq3;
Y3 = Y2+coupler*sinq3;
%Now plot the linkage...
line([X1;X2],[Y1;Y2],’Color’,’g’,’LineWidth’,1);
line([X2;X3],[Y2;Y3],’Color’,’r’,’LineWidth’,1);
line([X3;X4],[Y3;Y4],’Color’,’b’,’LineWidth’,1);

    %Coupler location
xca1(i) = crank*cos(theta2s(i))+toCouplerPoint*cos(q3+gammac);
yca1(i) = crank*sin(theta2s(i))+toCouplerPoint*sin(q3+gammac);

    %Compute coupler velocities.
dtheta2dt = 4.19; % in rad/s for 3V input with load, from force analysis

    if(i¿1)
dx = xca1(i)-xca1(i-1);
dy = yca1(i)-yca1(i-1);
velocities(i) = dtheta2dt.*sqrt(dx2̂ + dy2̂)/theta2step;
end

    %Plot Coupler
plot(xca1(i),yca1(i),’*’);
line([X2;xca1(i)],[Y2;yca1(i)],’Color’,’y’,’LineWidth’,1);

    end %end for i
```

```
xlabel('x-Dimension');
ylabel('y-Dimension');
title('Kangaroo Forelimb 4 Bar Linkage');
%% Plot the coupler velocities

figure;
plot(theta2s(2:end),velocities(2:end));
xlabel('theta2 (radians)') % x-axis label
ylabel('velocity (cm/s)') % y-axis label
title('Velocity of Kangaroo Forelimb Linkage');
```

E.2 Hindlimb Curves

```
%Hindlimb
clear all; close all; clc;

% Length of Linkages:
%Given in cm
% (in)*cm conversion
hindlimbconstant = 1.5;
frame = 6.5 * hindlimbconstant;
crank = 2.5 * hindlimbconstant;
coupler = 8.5 * hindlimbconstant;
rocker = 5 * hindlimbconstant;
toCouplerPoint = 10.5 * hindlimbconstant;
gammac = pi*(115/180);

%Define range of angles to plot and step size

theta2start = 0;
theta2end = 2*pi;
numsteps = 24;
theta2step = (theta2end-theta2start)/numsteps;
theta2s = [theta2start:theta2step:theta2end];
velocities = zeros(numsteps,1); %empty array

%Guess a reasonable plot area (may need to tweak these)
leftlim = -15;
rightlim = 35;
bottomlim = -15;
toplim = 15;
axis([-20 20 -5 20]);
grid('on')

%The fixed ground link
X1 = 0;
Y1 = 0;
X4 = frame;
```

```
Y4 = 0;
line([X4;X1],[Y4;Y1],'Color','k','LineWidth',1);

    hold on;

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Main loop for each crank angle
for i=1:length(theta2s)

    cosq2 = cos(theta2s(i));
sinq2 = sin(theta2s(i));

    % Define some substitutions (9.29-9.31)
A = 2*rocker*(frame - crank*cosq2);
B = -2*crank*rocker*sinq2;
C = coupler2̂ - crank2̂ - rocker2̂ - frame2̂ + 2*crank*frame*cosq2;

    %Solve for the roots of half angle equation (9.35)
%If general
u41 = (B + sqrt(A2̂ + B2̂ - C2̂))/(A+C);
q4 = 2*atan(u41);

    %Solve for theta3 (9.37-9.39)
%range = -PI to +PI
cosq3 = (-crank*cosq2 + rocker*cos(q4) + frame)/coupler;
sinq3 = (-crank*sinq2 + rocker*sin(q4))/coupler;
q3 = atan2(sinq3,cosq3); %don't really need it for plotting

    %Compute locations of joints 2,3
X2 = crank * cosq2;
Y2 = crank * sinq2;
X3 = X2+coupler*cosq3;
Y3 = Y2+coupler*sinq3;
%Now plot the linkage...
line([X1;X2],[Y1;Y2],'Color','g','LineWidth',1);
line([X2;X3],[Y2;Y3],'Color','r','LineWidth',1);
line([X3;X4],[Y3;Y4],'Color','b','LineWidth',1);

    %Coupler location
xca1(i) = crank*cos(theta2s(i))+toCouplerPoint*cos(q3+gammac);
yca1(i) = crank*sin(theta2s(i))+toCouplerPoint*sin(q3+gammac);

    %Compute coupler velocities.
dtheta2dt = 4.19; % in rad/s for 3V input with load, from force analysis

    if(i¿1)
dx = xca1(i)-xca1(i-1);
dy = yca1(i)-yca1(i-1);
velocities(i) = dtheta2dt.*sqrt(dx2̂ + dy2̂)/theta2step;
```

```
end

    %Plot Coupler
plot(xca1(i),yca1(i),'*');
line([X2;xca1(i)],[Y2;yca1(i)],'Color','y','LineWidth',1);

    end %end for i
xlabel('x-Dimension');
ylabel('y-Dimension');
title('Kangaroo Hindlimb 4 Bar Linkage');
%% Plot the coupler velocities

    figure;
plot(theta2s(2:end),velocities(2:end));
xlabel('theta2 (radians)') % x-axis label
ylabel('velocity (cm/s)') % y-axis label
title('Velocity of Kangaroo Hindlimb Linkage');
```

E.3 Tail Curves

```
clear all; close all; clc;

    % Length of Linkages:
%Given in cm
% (in)*cm conversion
frame = 4.5;
crank = 1.5;
coupler = 5.5;
rocker = 3.5;
toCouplerPoint = 13;
gammac = pi*(45/180);

    %Define range of angles to plot and step size

    theta2start = 0;
theta2end = 2*pi;
numsteps = 24;
theta2step = (theta2end-theta2start)/numsteps;
theta2s = [theta2start:theta2step:theta2end];
velocities = zeros(numsteps,1); %empty array

    %Guess a reasonable plot area (may need to tweak these)
leftlim = -15;
rightlim = 35;
bottomlim = -15;
toplim = 15;
axis([leftlim rightlim bottomlim toplim],'equal');
grid('on')
```

```
    %The fixed ground link
X1 = 0;
Y1 = 0;
X4 = frame;
Y4 = 0;
line([X4;X1],[Y4;Y1],’Color’,’k’,’LineWidth’,1);

    hold on;

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Main loop for each crank angle
for i=1:length(theta2s)

    cosq2 = cos(theta2s(i));
sinq2 = sin(theta2s(i));

    % Define some substitutions (9.29-9.31)
A = 2*rocker*(frame - crank*cosq2);
B = -2*crank*rocker*sinq2;
C = coupler2̂ - crank2̂ - rocker2̂ - frame2̂ + 2*crank*frame*cosq2;

    %Solve for the roots of half angle equation (9.35)
%If general
u41 = (B + sqrt(A2̂ + B2̂ - C2̂))/(A+C);
q4 = 2*atan(u41);

    %Solve for theta3 (9.37-9.39)
%range = -PI to +PI
cosq3 = (-crank*cosq2 + rocker*cos(q4) + frame)/coupler;
sinq3 = (-crank*sinq2 + rocker*sin(q4))/coupler;
q3 = atan2(sinq3,cosq3); %don’t really need it for plotting

    %Compute locations of joints 2,3
X2 = crank * cosq2;
Y2 = crank * sinq2;
X3 = X2+coupler*cosq3;
Y3 = Y2+coupler*sinq3;
%Now plot the linkage...
line([X1;X2],[Y1;Y2],’Color’,’g’,’LineWidth’,1);
line([X2;X3],[Y2;Y3],’Color’,’r’,’LineWidth’,1);
line([X3;X4],[Y3;Y4],’Color’,’b’,’LineWidth’,1);

    %Coupler location
xca1(i) = crank*cos(theta2s(i))+toCouplerPoint*cos(q3+gammac);
yca1(i) = crank*sin(theta2s(i))+toCouplerPoint*sin(q3+gammac);

    %Compute coupler velocities.
dtheta2dt = 4.19; % in rad/s for 3V input with load, from force analysis
```

```
if(i¿1)
dx = xca1(i)-xca1(i-1);
dy = yca1(i)-yca1(i-1);
velocities(i) = dtheta2dt.*sqrt(dx2̂ + dy2̂)/theta2step;
end

%Plot Coupler
plot(xca1(i),yca1(i),'*');
line([X2;xca1(i)],[Y2;yca1(i)],'Color','y','LineWidth',1);

end %end for i
xlabel('x-Dimension');
ylabel('y-Dimension');
title('Kangaroo Tail 4 Bar Linkage');
axis([-10 10 -5 15])

%% Plot the coupler velocities

figure;
plot(theta2s(2:end),velocities(2:end));
xlabel('theta2 (radians)') % x-axis label
ylabel('velocity (cm/s)') % y-axis label
title('Velocity of Kangaroo Tail Linkage');
```

E.4 Motor Characterization

```
clear all; close all; clc;

%Constants
radpersectoRPM = (1.*60)./(2*pi);
gearRatio = 196.7;
R = 1.05;
k = 0.0029;
V1 = 2.6;
myCurrent1 = 0.5;
myCurrent2 = 1.0;

% Predicted Omegas
predictedOmegaRPMFP = 24;
predictedOmegaFP = predictedOmegaRPMFP/radpersectoRPM
predictedOmegaRPMheuristic = 10;
predictedOmegaHeuristic = predictedOmegaRPMheuristic/radpersectoRPM

% Predicted Currents
predictedCurrentFP = (V1-(k.*predictedOmegaFP.*gearRatio))./R
predictedCurrentHeuristic = (V1-(k.*predictedOmegaHeuristic.*gearRatio))./R
```

```
    % No load current and omegas
inl = .15;
omeganl1 = ((V1-inl.*R)./k);
Tf = inl*k;

    % Stall current
istall1 = V1./R
Tstall = k*istall1 - Tf;

    % Torques at certain points
myTorque1 = (k.*myCurrent1 - Tf) .* gearRatio
myTorque2 = (k.*myCurrent2 - Tf) .* gearRatio
predictedTorqueFP = (k.*predictedCurrentFP - Tf) .* gearRatio
predictedTorqueHeuristic = (k.*predictedCurrentHeuristic - Tf) .* gearRatio

    % Current
i1 = linspace(istall1, inl,500);

    % Omega
myOmega1 = (((V1-(myCurrent1.*R))./k)./gearRatio)
myOmega1RPM = (((V1-(myCurrent1.*R))./k)./gearRatio).*radpersectoRPM
myOmega2 = (((V1-(myCurrent2.*R))./k)./gearRatio)
myOmega2RPM = (((V1-(myCurrent2.*R))./k)./gearRatio).*radpersectoRPM
omega1 = (((V1-i1.*R)./k)./gearRatio);
omega1RPM = omega1*radpersectoRPM;

    % Output Power
Tl1 = (k.*i1 - Tf) .* gearRatio;
P1 = Tl1.*omega1;
myPower1 = myTorque1.*myOmega1
myPower2 = myTorque2.*myOmega2

    predictedPowerFP = predictedTorqueFP.*predictedOmegaFP
predictedPowerHeuristic = predictedTorqueHeuristic.*predictedOmegaHeuristic

    % Peak Power
ipeak1 = 0.5.*(inl + istall1);
Ppeak1 = (k.*ipeak1 - Tf).*(V1-ipeak1.*R)./k

    % Efficiency
eff1 = Tl1.*omega1./V1./i1;
myEfficiency1 = myTorque1.*myOmega1./V1./myCurrent1
myEfficiency2 = myTorque2.*myOmega2./V1./myCurrent2

    predictedEfficiencyFP = predictedTorqueFP.*predictedOmegaFP./V1./predictedCurrentFP
predictedEfficiencyHeuristic = predictedTorqueHeuristic.*predictedOmegaHeuristic./V1./predictedCurrentHeuristic

    %% Plots
```

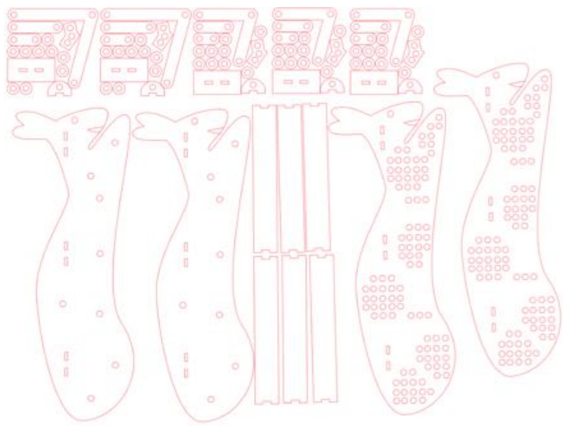
```
% Plot of output power vs omega
plot(omega1RPM,P1);
hold on
title('Output Power vs. Omega');
xlabel('Omega (RPM)');
ylabel('Power (Nm/s)');
plot (myOmega1RPM, myPower1,'ko');
plot (myOmega2RPM, myPower2,'ro');
plot (predictedOmegaRPMFP, predictedPowerFP, 'b*');
plot (predictedOmegaRPMheuristic, predictedPowerHeuristic, 'm*');
legend('Power', 'general operating point', 'high stress operating point','Predicted high stress operating point (Force Plate)','Predicted high stress operating point (Heuristic)','Location','South');

% Plot of Torque vs omega
figure
plot(omega1RPM, Tl1);
hold on;
title('Torque vs. Omega');
xlabel('Omega (RPM)');
ylabel('Torque (Nm)');
plot(myOmega1RPM, myTorque1,'ko');
plot(myOmega2RPM, myTorque2, 'ro');
plot (predictedOmegaRPMFP, predictedTorqueFP, 'b*');
plot (predictedOmegaRPMheuristic, predictedTorqueHeuristic, 'm*');
legend('Torque', 'general operating point', 'high stress operating point', 'Predicted high stress operating point (Force Plate)','Predicted high stress operating point (Heuristic)');

% Plot of Efficiency vs. Omega
figure
plot(omega1RPM, eff1);
hold on;
title('Efficiency vs. Omega');
xlabel('Omega (RPM)');
ylabel('Efficiency');
plot(myOmega1RPM, myEfficiency1, 'ko');
plot(myOmega2RPM, myEfficiency2, 'ro');
plot (predictedOmegaRPMFP, predictedEfficiencyFP, 'b*');
plot (predictedOmegaRPMheuristic, predictedEfficiencyHeuristic, 'm*');
legend('Efficiency', 'general operating point', 'high stress operating point','Predicted high stress operating point (Force Plate)','Predicted high stress operating point (Heuristic)','Location','South');
```

F Parts Required and To-Scale Drawings

F.1 Laser Cut Parts



(a) Wallaby One. Dimensions: 24" Wide x 18" Tall.

(b) 4-bar Linkage Limb Components of Kangaroo 2. Dimensions: 3.5" Wide x 4" Tall.

Figure 40: Laser cutter shapes.

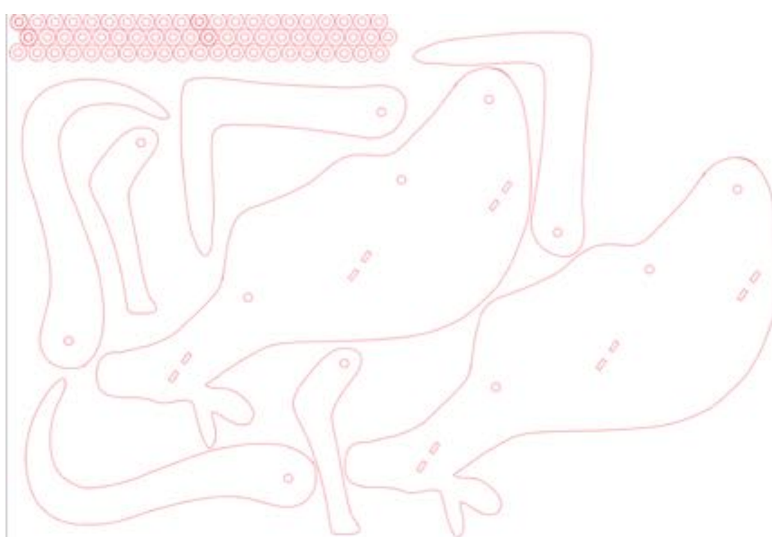
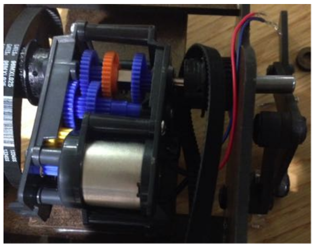
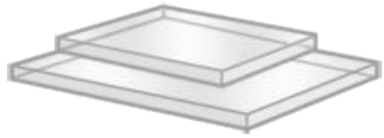


Figure 41: Kangaroo Two. Dimensions: 16" Wide x 12" Tall

F.2 Other parts

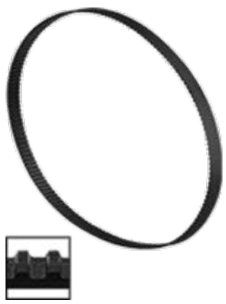


(a) Tamiya 72005 6-Speed Gearbox Kit.

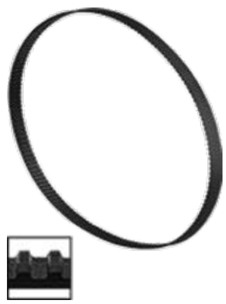


(b) 0.25" acrylic.

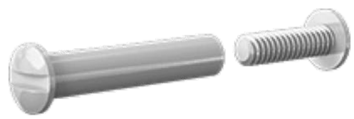
(c) Flanged Bearings. 0.25" Inner Diameter, 0.375" Outer Diameter.



(d) Timing Belts. 10.4" Diameter.



(e) Timing Belts. 12.4" Diameter.



(f) Binding Posts (1" long, 0.25" diameter).

(g) 0.25" hollow steel shafts, 6" long.

(h) Timing Pulleys. 0.744" OD.

(i) Twin AA Battery Holder. 1.5" wide, 2.5" tall, 0.5" deep.

(j) 0.375" length by 0.1" diameter nails (used as pins).

(k) Bike tire tubing.