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IMPROVEMENT OF CHEETAH-CUB LOCOMOTION BY A NEW FOOT DESIGN

SEMESTER PROJECT

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Abstract:

In this report, we explain the development and the test done on a new foot design for the quadruped robot Cheetah-Cub, developed at Biorobotics Lab, EPFL. This design, based on simple mechanical features extracted of a biological model, is assessed in term of speed and stability. It is built by SLS 3D printer and shows flexible beam instead of standard rotational joint, in order to improve its energetic properties in term of conservation. The most important parameters of this new design are its independently articulated toes, the added tarsal-metatarsal joint and a compliant heel, that hypothetically have important impacts on the locomotion of the robot. The CPG driven robot allow us to test several gait and to perform a grid search for good locomotion parameters, achieving, at the end, a top speed of ***0.72 m/s.*** *The importance of some locomotion parameters, especially the hind hip offset are demonstrated and their impact quantified. The predicted benefits that the toes might have on the stability are rejected since the robot shows higher RMS pitch and roll value during walking gaits than it does using the old version of the feet. Interesting results concerning the joint stiffness are shown. The variability of the stiffness against the speed are explained and some design principles are proposed at the end of the report exploiting this specific parameter.*

1 INTRODUCTION

Locomotion in quadrupeds is achieved by multiple mechanism. In particular, beside a very clever control system and whenever they are not fully understood yet, the biomechanics of their limbs should play an important role in fluent and efficient displacements. Nowadays, the roboticians try to approach these mechanisms by creating robots that mimic their most important features. Especially, a lot of work have been done on the robot leg design, based on the SLIP model of mammal limbs: legs with one to three segments have been developed, achieving movements that are close to the real locomotion patterns in quadrupeds.

One great success of this kind of approach is the Cheetah-Cub robot of the Biorob Lab EPFL [11]. This small robot, weighting 1.4kg for 25cm, is the fastest quadruped robot under 30kg. It embeds only two motors per leg, that are fixed on the robot main structure, reducing the inertia of the limbs, which permits to achieve these performances. These legs are based on a pantographic model. Two springs, one diagonal and one parallel, are added in order to add compliancy and passive dynamic behaviour. This new model is called ASLP. The robot's control is done with a CPG (Central Pattern Generator) controller in open-loop (no sensory feedback, but it remains a regulation loop on the servos position) and the compliance of its limbs is done through mechanics, as it is implemented in biological systems. Regarding these facts, it seems that leg passive behaviours could be one of the key in efficient locomotion

But, therefore and if the will is to approach as close as possible the biological behaviour, the mechanic of the cheetah-cub robot isn't complete. Looking at real natural systems as dog or cheetah, one can observe that a part of the energy is given back by the feet of these animals at the end of their stance phase. Little of the bio-robotical applications take this fact in account. Cheetah-Cub does embed specialized feet, but they are not close to the real structural anatomy of the cited mammal. Actually, the feet of this robot consist in an additional flat distal segment to the ASLP legs.

We hypothesised that implementing bio-inspired feet, by changing the design of the existing ones and making it closer to real anatomy, could improve the locomotion of this robot, in term of speed and stability.

This project aim to develop and test these new feet on the cheetah-cub robot. By looking at animal morphologies, the important features embed in these structures should be extracted and. From this point, a new foot design could be built and experiments run, in order to verify the previous hypothesis. We present in this report, the design process of five new feet showing three independent toes, a compliant tarsal-metatarsal joint and a compliant paw. The toes add a compliance to the robot against small perturbations. On rough terrain showing irregular levels, this solution could improve the stability, because offering a wider ground contact (each toe should constantly be in contact with it, see figure 5) and not a punctual one, as it is currently the case. Adding a torsional behaviour could permit an even better contact and move closer the design to real systems.

The report begins by presenting the state of the art in feet design in section 2. Subsequently, the methodology of the project is described in four steps, from observation of biological systems to the analysis of the acquired data, in section 3. In section 4, the results obtained in term of speed and stability are shown. The discussion take place in section 5. We conclude this report by giving some potential future work and possible bettering on the actual design in last section 6. Appendices comport some details of the design process and the table of the results of several experiments.

2 STATE OF THE ART

The actual mostly used design in robot's feet is the standard cylinder/ball shape. Most of the quadruped robot that achieve good control performances are mounted with this kind of feet. The reason to this particularly important use is that it allows to add some kind of sensors under the feet and, therefore having feedback signal, ended in very impressive control. The most impressive achievement in this kind of robot are surely the Boston Dynamics *Spot* and *Big Dog*. Some others interesting feeded-back robot are developed in Switzerland like SarlETH, that, using touch sensors feedback , can steady navigate in rough terrain. Using compliant feet might cause some problem in the addition of sensors, since it might be difficult to technically integrate it, but overall, it surely necessities a more complex model in order to extract decisive information.

At the moment, few robots have specialized feet. The existing ones that embed specialized feet (i.e. a dedicated mechanical structure that is built-in the robot to mimic a foot) show essentially an additional small compliant distal segment at the end of their limbs, as it is the case it the Cheetah Robot from MIT Biomimetic Lab, EPFL BioRob Lab and HRL Laboratories.

Figure 1. *Some feet implementation in quadruped robots.* ***Left:*** *MIT Cheetah robot* ***Middle:*** *Cheetah-Cub BioRob Robot* ***Right:*** *HRL Laboratories*

Nevertheless, these type of structures showed better performances of the robot in term of speed. (Spröwitz, 2013) show that the standard cylinder-shaped feet was 10% less efficient as the ASLP version shown in figure 1 (middle), because increasing the length of the limbs at toe-off and releasing energy at the very end of the stance-phase.

Notably, we can cite the previous work done in the BioRob Lab for another semester project [?].

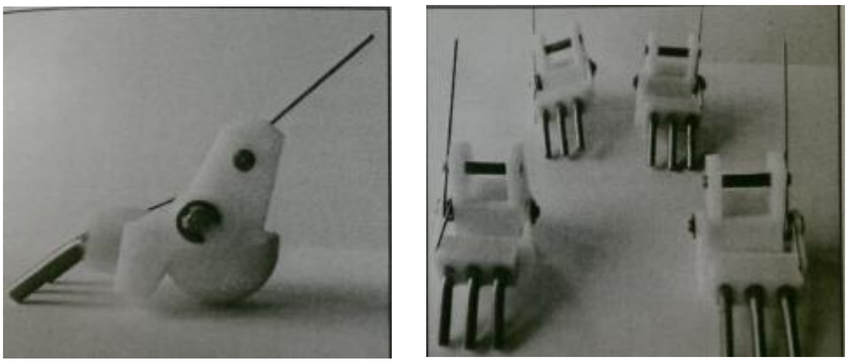


Figure 2 *First prototype for the cheetah-cub specialized feet. We can see the 3 claws at the front of the feet and the round shape "heel". As it was built in ABS this structure were not compliant.*

They developed a foot that is articulated at the tarsal-metatarsal joint and metatarsal-distal joint (we will call it the *toe joint* in the following text) (Figure 2). These joints are made compliant by the use of a rotational spring, integrated in the design. Moreover, some claws have been added in order to increase the gripping of the feet on the ground. They planned to create a smooth "heel", such that the energy of the contact shock at the first touch in the stance phase could be absorbed directly in the foot. It has not been done neither tested, unfortunately.

The impacts of these feet to the robot locomotion were not satisfying. They observed almost the same performances in term of speed but the stability was decreased on soft terrains. The hypothesis to explicit these observations was that the claws tended to grip too much to the ground, prolonging the stance phase and therefore inducing a loss stability. Moreover, the claws implied a 3 points discrete contact with the ground in paw-off phase (i.e. the moment when the feet leave the ground). This implied a loss of adherence of the feet and, thus, an undesirable slippery effect that reduced the robot propulsion. Based on these observation, the design the will be assessed in this report should take these problematic points in account and manage to avoid it.

3 MATERIAL AND METHODOLOGY

This project was based on the CPG driven Cheetah-Cub robot from BioRobotics Lab, EPFL. This platform, due to the parametric form of its controller, allowed us to test several configurations and, therefore, numerous gaits. Two motor per legs permitted to control the robot footfall pattern, acting essentially on the hip movement amplitude and knee compression. It also embed an articulated tail that can be parameterized in the CPG as well. Details concerning the parametric changes are explained in following subsection 3.3. All details on the robot architecture and CPG parameters can be found in [11].

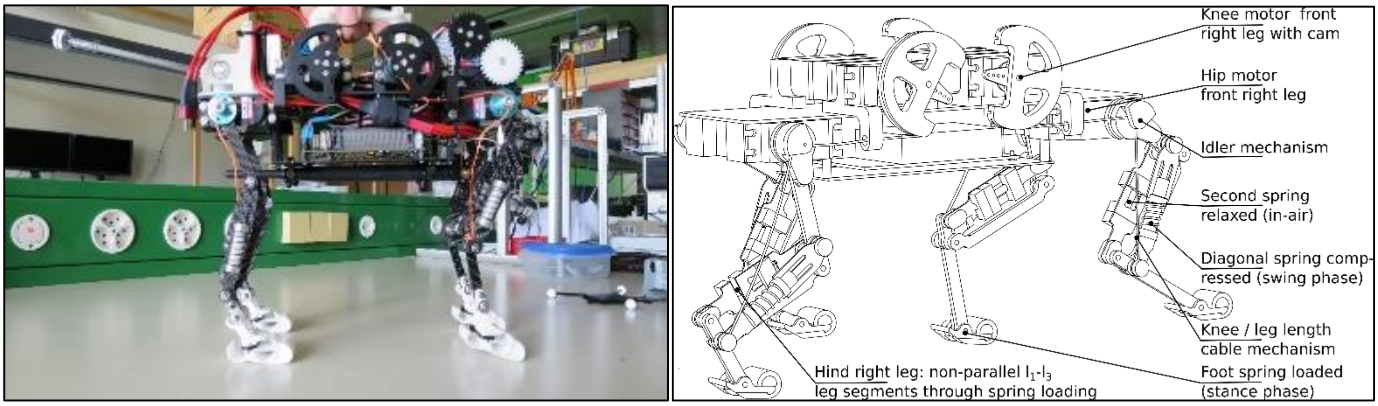


***Figure 3** Cheetah-Cub Robot configuration. New Configuration with designed feet and descriptive mechanism of the robot. Images: Biorobotics Lab, EPFL*

According to [6], that describes a systematic approach in bio-inspired engineering, the methodology of this project was articulated around four main steps in order to produce the first iteration of a design principle for a bio-inspired robotic foot

3.1 Observation of the biological systems

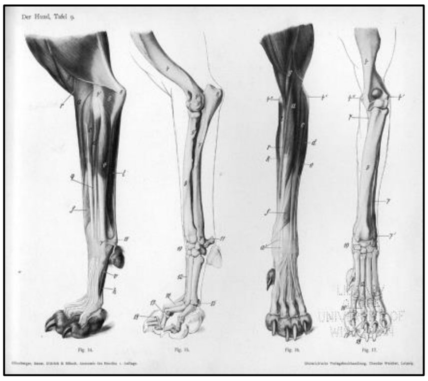


***Figure 4** Anatomical sketch of a cheetah forelimb*

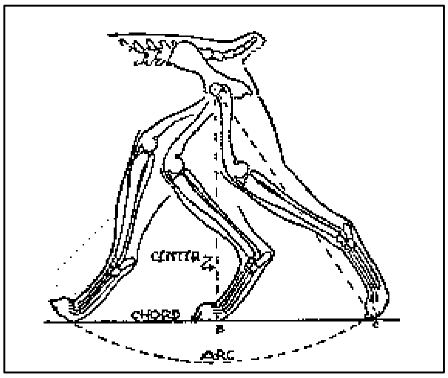


***Figure 6** Hind limb flexion pattern*

First step was to observe the mechanics in real biological systems. This process was done on an anatomical model of digitigrade (cat, dog, cheetah) feet found in literature [9], with the aim to extract the simplest structural mechanics that was not present on actual cheetah-cub feet. Two principal aspects were deepened: joint mechanics and gait control. We observed that the current feet of cheetah were built in a single unarticulated flat toe whereas the actual feet of these mammals showed 4 independently articulated toes and a compliant tarsal-metatarsal joint (Figure 5).The bottom of the paw of these mammal were moreover observed as soft and compliant. Following the observation of several gait videos of cats and cheetahs, some control principles were deduced. In particular, we figured out that digitigrades mammal always touch the ground with the back of the paw (i.e. let call it heel), and that toe's flexion only occurred at the very end of stance phase (Figure 6). On the other hand, the controller of the Cheetah-Cub tended to make the tip of the feet touch first. Last observation: the considered mammals showed soft paws whereas Cheetah-Cub only performed hard contact with the ground. We wanted to implement all these specific mechanics and control principles in the new version of the feet. The design principles related to these observations are presented in following subsections

3.2 Translation of common features in an engineered model and design

Second step was to traduce these anatomical mechanism in an engineering technical model, that could be built in accessible manufacture technologies. A trial and error approach was chosen in order to achieve a good design principle. As the design should be coherent regarding the previous observations, the cited mechanics were simplified into a standard joints model (Figure 7). Regarding [8] assumptions, a strong look was putted on the energetic efficiency of the design and an innovative solution based on flexible joints, in replacement of standard rotational joint, was proposed (Figure 8).This joint were based on the elastic behaviour of materials (Hook Law).They were essentially built as some flexible blades that deformed under a given charge (Beam Deformation Theory) (Figure 8).The advantages of using this kind joint are that they essentially dissipate less energy by friction as the standard rotational joints, since it is a contactless displacement. Since a little amount of data concerning stiffness of digitigrades ankle and toe joints was available, the dimensions of the spring constants related to these flexible blades were chosen roughly the same as in the existing functional feet of cheetah-cub (4.5N/m). The computation of flexible blades spring constant is available in appendix I. Four versions of the feet were designed, showing different mechanical properties, essentially in term of joint's stiffness (9, 7, 5, 3 N/m).These variations in stiffness were achieved by changing the thickness of the blades (1.1, 1, 0.9, 0.8mm). Tarsal-metatarsal joint

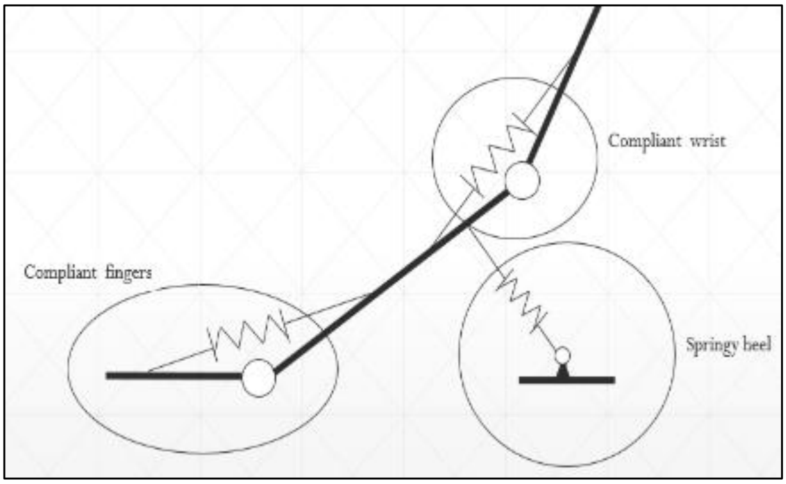


***Figure 7** Mechanical model of the new feet. Transversal cut. There are 3 compliant fingers in parallel based on the mechanic principle shown in this figure. All the springs in this figure should work in compression mode. Compliant wrist and fingers amplitudes should be limited to ± 10° and +30° from rest position, respectively. This was practically done.*

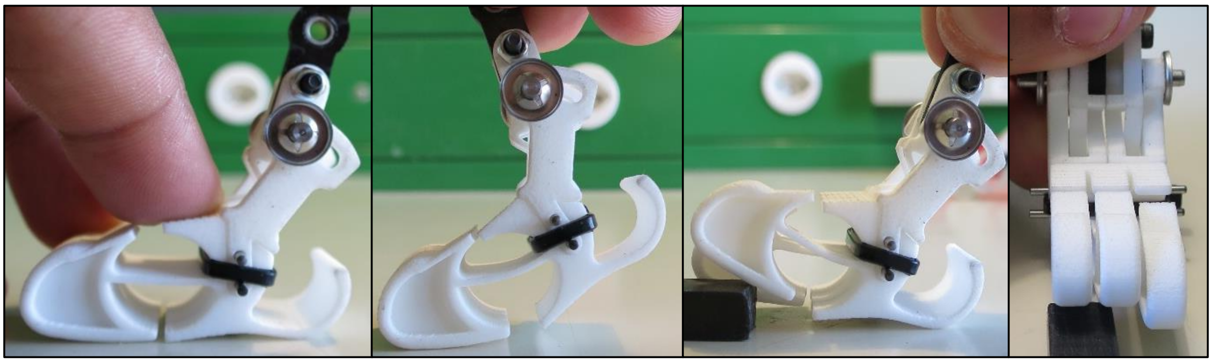
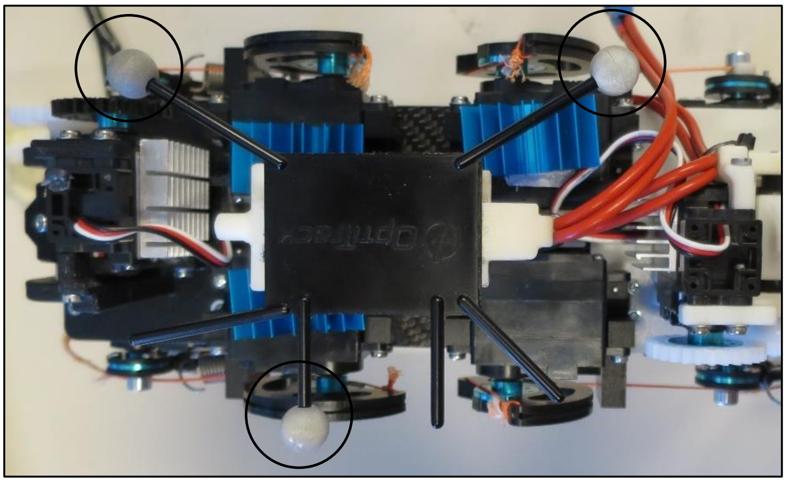


***Figure 8** Final design with 9 N/m (1.1mm thick) flexible blades for fingers joints. Springy heel and compliant metatarsal mechanics are also replaced by a flexible blades. One can observe the 30° compliancy of the toes. In contact with small objects, the dissociated fingers adopt a conformation with a good contact surface, which could lead to a good stability. The metatarsal joint show a maximum possible bending angle of ± 15°.*

stiffness was supposed being very low, since we observed an important displacement in this joint, when looking at the biological systems. We then fixed arbitrary its stiffness value at ¼ of the toe joint stiffness. The possibility to completely lock this joint was kept open by the design in case of malfunction. The manufacture of these pieces was done by 3D SLS printer in AFA workshop at EPFL. The feet were assembled in BioRobotic Lab workshop. Moreover, new control principles were hypothesized: The hip amplitude should be increased, such that the angle of attack increases as well and, thus, the heel touches the ground first. A consequent time was attributed to create a proper design according to this model. Details of the design process can be found in appendix I.

3.3 Testing the hypothesis: Data Collection

*Figure 9 Solid body used in tracking experiments mounted on Cheetah-Cub's back. The 3 infrareds reflective markers are circled in red: Top Left: **Front** Marker Top Right: **Back** Marker Bottom: **Side** Marker. We tried to align the two top markers with the edges of the robot structure in order to obtain a good information of roll and pitch for the further analysis of the stability*



In order to verify the improvement of the robot speed and stability due to the new design against the existing solution, a systematic search for good gait parameters was performed using the new feet. Firstly, the measurements were done on a flat and smooth surface (the ground), using a laboratory power supply, a constant voltage of 10V and a 14A limited current. The robot controller parameters were calibrated and modified through its dedicated interface (SSH and SFTP protocols).The calibration step imposed an absolute maximum and minimum amplitude of $\pm 45°$ to all the hip servos, full extension and compression

First Trotting Gait Parameters			
Fore Hip Amplitude	40	Left Fore-Hind Hip Phase lag	$\pi/2$
Fore Hip Offset	0	Right Fore-Hind Hip Phase lag	$\pi/2$
Hind Hip Amplitude	40	Left Fore- Right Fore Hip Phase lag	$\pi/2$
Hind Hip Offset	0	Left Hind- Right Hind Hip Phase lag	$\pi/2$
Fore Knee Amplitude	1	Tail Offset	10
Fore Knee Offset	0	Tail Amplitude	0
Fore Knee Stance Deflection	0.2	Tail Frequency	0
Hind Knee Amplitude	1		
Hind Knee Offset	0		
Hind Knee Stance Deflection	0.2		
For Hip-Knee Phase Lag	-0.3		
Hind Hip-Knee phase Lag	-0.3		

Table 1 First trotting gait parameters: They were found by testing the robot on the ground and visually evaluating the gait. These parameters were chosen as a good starting base since they permitted to achieve good angle of attack of the feet and speed. The parameters related to the tail of the robot set it in a steady vertical position. They were chosen this way because we observed this comportment in real cat during trotting gait.

lengths of 10 cm and 7cm for front knee and 12cm and 8cm for extension and compression length at hind knee servos. Thereafter, Cheetah-Cub was started and let freely run on the ground in a trotting gait. The trajectory were tracked in the plane using the infrared *Motive OptiTrack* motion capture system (tracking system disposition is described in [11]). This system took images of a solid body (i.e. 3 points infrared reflective markers of invariable size, Figure 9) fixed on the robot’s back, at a rate *r =250 fps,* with a precision of more or less *0.1mm*. The tracking begun at a start signal and ended at a stop signal (given by the experimenter), that corresponded to the first step of the robot on the ground and the lift off by the experimenter, respectively. Some recordings should be cleaned and resized using *Mokka* software.

A first satisfying gait of the robot was found (Table 1) by testing and based on old setup. Subsequently, we chose to test only fore and hind hip amplitudes and offsets, in order to have a limited number of open parameters. These four variables were varied with 5° steps in the *[35°; 45°]* and *[-5°; 5°]* ranges respectively. Thus 81 gaits have been tested systematically. These experiments were realized, at first, with the stiffest feet (9 N/m, 1.1mm thick flexible blades). We added sandpaper under the feet in order to increase their friction coefficient, since we observed slippery effects that lead to no forward motion. Then, the 6 fastest gait were statistically tested using 3 types of new feet (1.1mm, 1mm and 0.8mm: 9,5,3 Nm/° respectively) (hypothesis) and the old ones (control). Each gait was repeated 10 times for each new feet’s type and 5 times for the old ones. The results of 210 runs are presented in section **4.2.3**. Verification runs were performed using the old feet and the slowest gaits in order to validate the observed bettering of the new feet, in any case.

3.3.1 Speed extraction

The speed of the robot for each gait could be extracted from the *.c3d* files provided by the tracking software, using a python script and the *BTK* package that can be found in appendix [?]. The position of the robot in X and Y axis were extracted in frame 200 and 600 (pos_{y200} and pos_{y600}) from markers and the speed computed as the first order approximation between these two points. The motivations of this choice were the facts that the robot could reach a stable speed in the 200 frames and that a good linear approximation should be done in a small time period.

$$S = \frac{\left(pos_{y600} - pos_{y200}\right)}{\left(\frac{400}{r}\right)} \qquad (1)$$

3.3.2 Stability extraction

For each robot runs, the ones that lead to a fall of the robot were systematically reported. These kinds of events were the sign of an instability of the robot. Moreover, some stability measures were computed from the previously presented tracking data. We based the analysis of this behaviour on the roll and pitch variations during the trotting gait. These values gave us an idea of the variability of the robot body position compared to a perfectly steady one. We could extract these information from the solid body markers positions in the Z-axis. Since they were almost sinusoidal, the RMS value of the roll and pitch amplitudes were computed, in order to obtain a non-zero mean. I is the total number of frame used in the approximation, *i* is the index of the frame. This calculation was done for each run of all experiments.

$$Pitch_i = Front_{Zi} - Back_{Zi} \qquad (2)$$

$$Roll_i = \left(\frac{2}{3} * Pitch_i + Back_{Zi}\right) - Side_{Zi} \qquad (3)$$

$$Pitch_{mean} = \frac{1}{I}\sum_i Pitch_i \qquad (4)$$

$$Roll_{mean} = \frac{1}{I}\sum_{i} Roll_i \qquad (5)$$

$$Pitch_{RMS} = \sqrt[2]{\frac{1}{I}\sum_{i}(Pitch_i - Pitchmean)^2} \qquad (6)$$

$$Roll_{RMS} = \sqrt[2]{\frac{1}{I}\sum_{i}(Roll_i - Rollmean)^2} \qquad (7)$$

3.4 Analysis Method

At first, in order to qualitatively assess the performances of the robot during the different gait, several slow motion videos were taken. An analysis of the robot's coordination, as well as the angle of attack and stability were observed. The aim was to compare the observations made on these videos with the actual predictions that we made. We could extract some astonishing behaviour that are explained in section 4.1.1.

Statistical analysis were performed on the speed and stability data. The normality of the speed distribution over the parameters were tested, in order to validate the necessary hypothesis of the further analysis. The significance of the parameters was evaluated using an 4-way ANOVA process in Matlab (version R2014a) with the *anovan()* function. This function essentially performed an F-test on the data. This method was particularly well adapted, since every subset of parameters had the same number of sample. The evaluation was done on the 81 speeds, roll means and pitch means, obtained from the first systematic search. The 4 explicative parameters were the 3 level variables foreamplitude, foreoffset, hindamplitude and hindoffset and the explained values was the speed. The output value of the ANVOA analysis was an F-value for each parameter and combination of parameters. The level of validation (decision rule) was fixed at 0.05, meaning that the F-Value should be smaller than this level in order to accept the hypothesis that the parameter had a significant effect on the tested value. The parameters that showed having the widest effect on the speed were taken in a multiple comparison (function *multcompare()*), in order to observe the effect of their combination. Thereafter, a Repeated Measure ANOVA was performed between the measures done with the 4 different types of feet, aiming to extract a significant effect related to the finger joint stiffness and structural design. In this evaluation, we considered that the 6 chosen best gaits were all issue from the same speed distribution, a correct assumption regarding the results in 4.2.2. Finally, an evaluation of the stability was performed using the same statistical method. The effects of the stiffness of the toe joints on the robot pitch and roll variations was observed.

4 RESULTS

The following results are based on experiments done with the pantographic leg, but were not done in a raw. Actually, we should regularly change the legs for another project experiments on the same robot, and therefore change the configuration. When returning to the pantographic legs, some parameter might have slightly changed inducing potential variance in the results for a same evaluation. We tried as much as we could to reduce these possible variability in configuration.

We did 300 runs using the Cheetah-Cub robot and tracking its position is space. 81 were done for a grid search in order to find gait achieving stable motion and satisfying speed. The initialisation of this grid search was done by experimental research on the CPG parameters. 210 others runs were performed and tracked using a motion capture system, in order to build statistical analysis in term of speed and stability as well. This section present the results that we obtained according to the analysis strategy explained in **3.4**

4.1 Experiments observations

4.1.1 Design and gait

The experiment were started with the initial design configuration: tarsal-metatarsal joint was free to move and unconstraint. This configuration caused a dramatic issues. The robot was not able to trot at all because of the too low stiffness of this joint. Therefore, we chose to completely lock this joint, using a screw, in the maximum -15° position (Figure 10). All the further experiments were done with this configuration, allowing us to essentially assess the single effect of the disjoint toes and compliant heel.

***Figure 10** Locked Tarsal-Metatarsal joint in -15° position. The screw behind the moving axis (star-locker) blocks the joint movement.*

Looking at the slow motion videos, we could observe two important behaviour: Firstly, the heel did not seem to bend at the paw strike. This part should therefore have no improving effects on the speed. Secondly, we saw the robot did not achieve a correct trotting gait. Actually, it did something that was closer to a walking footfall pattern. Nevertheless, we tried to correct this problem by changing the phase lag parameters between the four legs. We did not achieved to obtain a correct trotting gait, even after several trials with multiple parameters.Therefore, in the following section, in order to be consistent, the results are compared with the walking gate performances obtained at the same frequency. We moreover observed that a small changing in voltage (10V to 9V) leads to dramatic consequences in the gaits. The robot could not even achieve one correct gait cycle in the low voltage setup. At first, we tested the robot using the pantographic legs and the initially mounted diagonal spring (?N/m) (Figure 3). We noticed an impossibility for the robot to achieve a dynamic gait. Therefore, we changed these springs for stiffer ones (3.5 N/m). The robot could thereafter run correctly. This changing implied a side effect: The legs were slightly bent in the inside, therefore, the feet were not perfectly parallel to the ground anymore.

4.2 Data Analysis

4.2.1 Speed – Grid Search

81 gaits were investigated. This section relate their performances in term of speed, without taking account of the parameters that were used. The effects of the parameters on the speed performances are shown in section 4.2.2. The table containing the parameter setups is shown in appendix III.

The speed is very variable. It ranges between 0.2 m/s for gait 67 and 70, up to 0.64 m/s, at top speed, for gait n°20. This represent almost a 90% amelioration by only changing a few parameters in a limited range. The six top speed gait are the *14, 20, 23, 26, 47, 72* with *0.63m/s, 0.64m/s, 0.61m/s, 0.61m/s, 0.6m/s* and *0.62m/s* respectively. They all show a hind hip offset at 0°. The principal parameter that vary between these 6 gaits is the hind amplitude. These gaits are deeply investigated in section 4.2.3, in statistical analysis.

4.2.2 Speed – Parameters effects

The results presented on this section were obtained using the data of the 81 first run, done during the systematic search of parameters. Each level of each parameter contained 27 samples.

Table 2 *F-Values obtained from the ANOVA analysis of the open parameters on the speed. A value smaller than 0.05 indicate that the parameter have a significant effect on the speed distribution (i.e. its levels have significantly different means)*

ANOVA F-Values	
Fore Amplitude	0.048
Fore Offset	0
Hind Amplitude	0.3316
Hind Offset	0
Fore Amplitude* Fore Offset	0.1719
Fore Amplitude*Hind Amplitude	0.7711
Fore Amplitude* Hind Offset	0.0013
Hind Amplitude* Fore Offset	0.6811
Hind Amplitude*Hind Offset	0.0248
Hind Offset * Fore Offset	0.9064

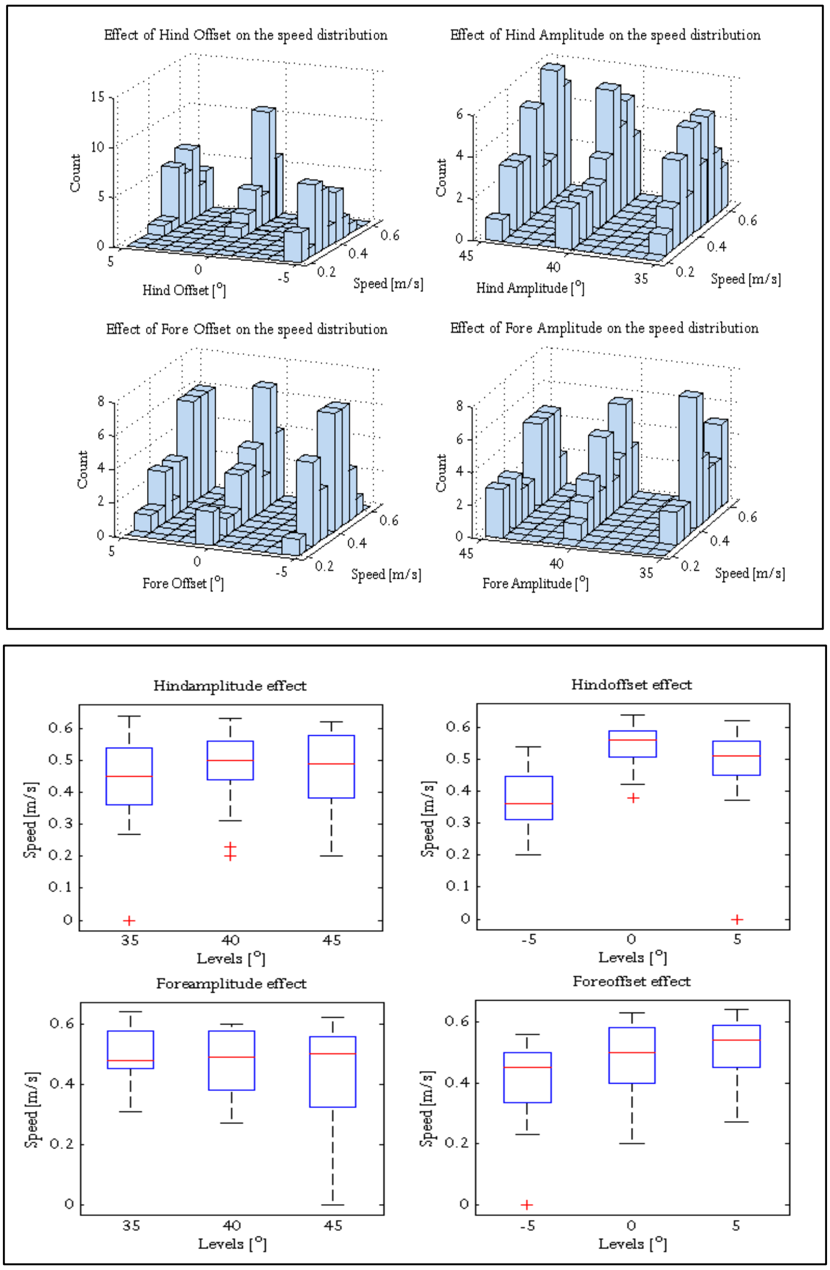


Figure 11 *Effects of the parameters on the speed. __Top__: Histogram of the speed distribution for the different parameters levels. __Bottom__: Median and 1st quartile and 3rd quartile for every open parameters. Outliers measures are the red crosses*

Table 2 reports the F-Values of the ANOVA analysis. With a 0 F-Value, Fore Offset and Hind Offset are clearly independently influent on the speed whereas, with a 0.9064 F-Value, their combinations are not different one from the others. The Fore Amplitude is very close to the limit (0.048) and Hind Amplitude is non-significant (0.3316). The important combination of parameters to evaluate is Fore Amplitude* Hind Offset (0.0013). The Hind Amplitude having no effect on the speed, its coupling with the Hind Offset is probably mostly influence by the Hind Offset, giving this F-Value (0.0248). Figure 11 shows the impact of each parameters on the speed performances. In histogram plots, we can observe that the first assumptions that we made concerning the normality of the speed’s distributions among the different parameters seems to be verified, which validate the analysis method we chose. Moreover, the boxplot show that the median of almost every distribution are well centred, which is desirable for normal distributions. Only the Hind Offset levels shows obvious mean differences among its levels in these plots.

Figure 12 shows the means of the speed distribution in function of the parameters levels. The speed shows a decreasing linear behaviour with the amplitude of the fore hip. The performances are 10% better when the fore amplitude is set at *35°* then at *45°*. As well, the fore hip offset seems to by linearly related to the speed. Best speeds are achieved using a *5°* fore hip offset, with a mean speed of *0.51 m/s,* which is *18%*

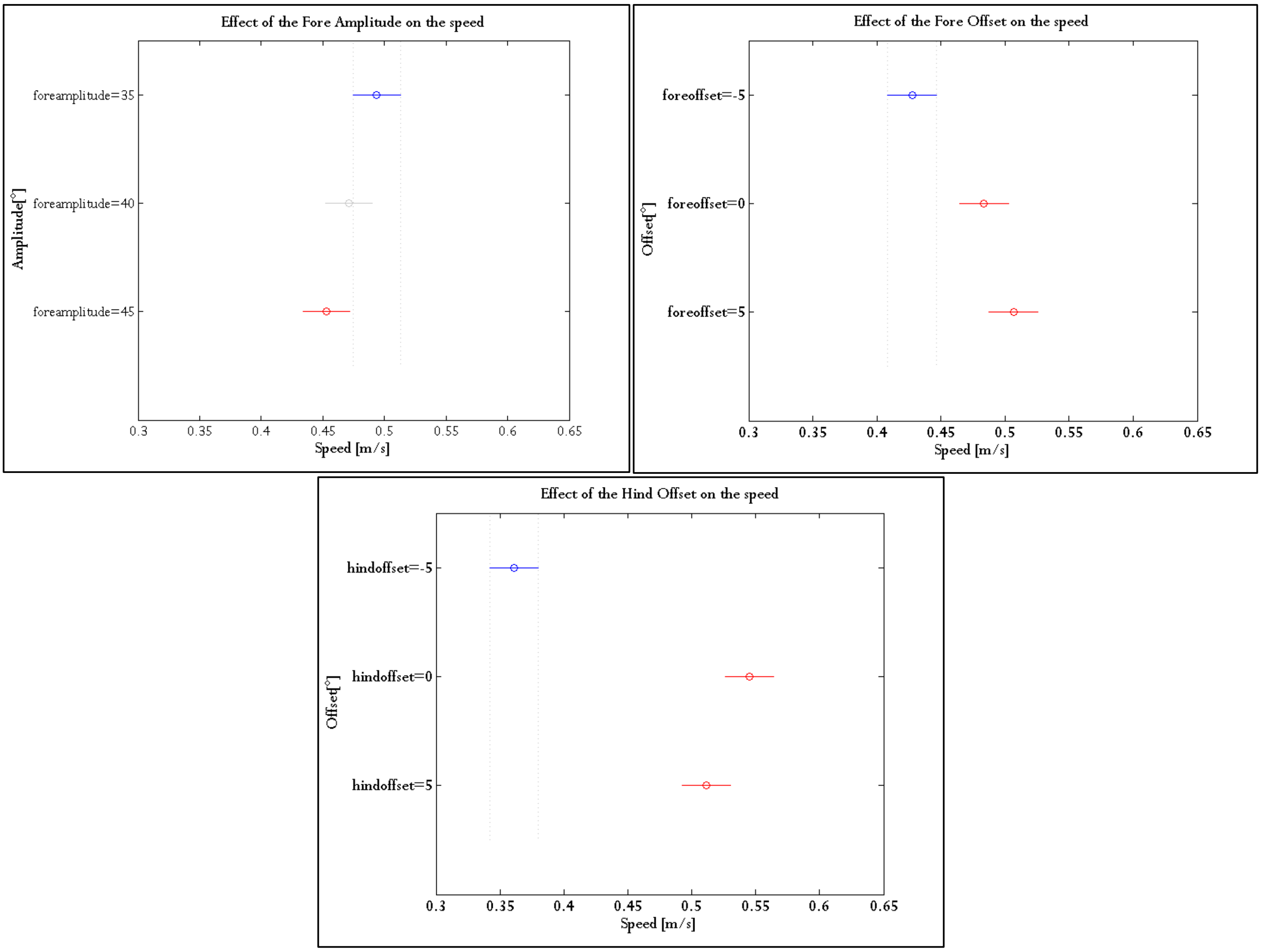


Figure 12 *Multi-comparison between the marginal means and interval s of the 3 most influent parameters. The blue lines are the population that are significantly different from the others, in red. The intervals give the information of the significant difference between two variable levels. If the interval are disjoint, the variable level are significantly different. (The interval size are computed on the base of the distribution variance)*

better than a *-5°* fore offset. The more distinctive effects are due to the hind hip offset (the F-Value analysis informed us already). The *-5°* level leads to statistically less good speed results with a mean around *0.35 m/s*, when the best, *0°* offset, leads to very well located speeds around *0.55 m/s*. This represents a *57%* bettering. On the other hand, the two best levels for this parameter (0° and 5°) are not significantly different in terms of mean. These results allow us to generally consider that the 6 best gaits are almost all arise of the same speed distribution, since the most influent parameter (hind offset) does not vary among these gait and is fixed at 0°. This assumption is afterwards cited as **Assumption 1.**

4.2.3 Speed – Feet Design Effects

In this section, we report the observations related to the effects that the changing in stiffness of the toe joints implies on the speed results. These results are based on 210 runs, 60 performed with each new feet (i.e. 10 for each best gait described in 4.2.1) and 30 with the old ones.

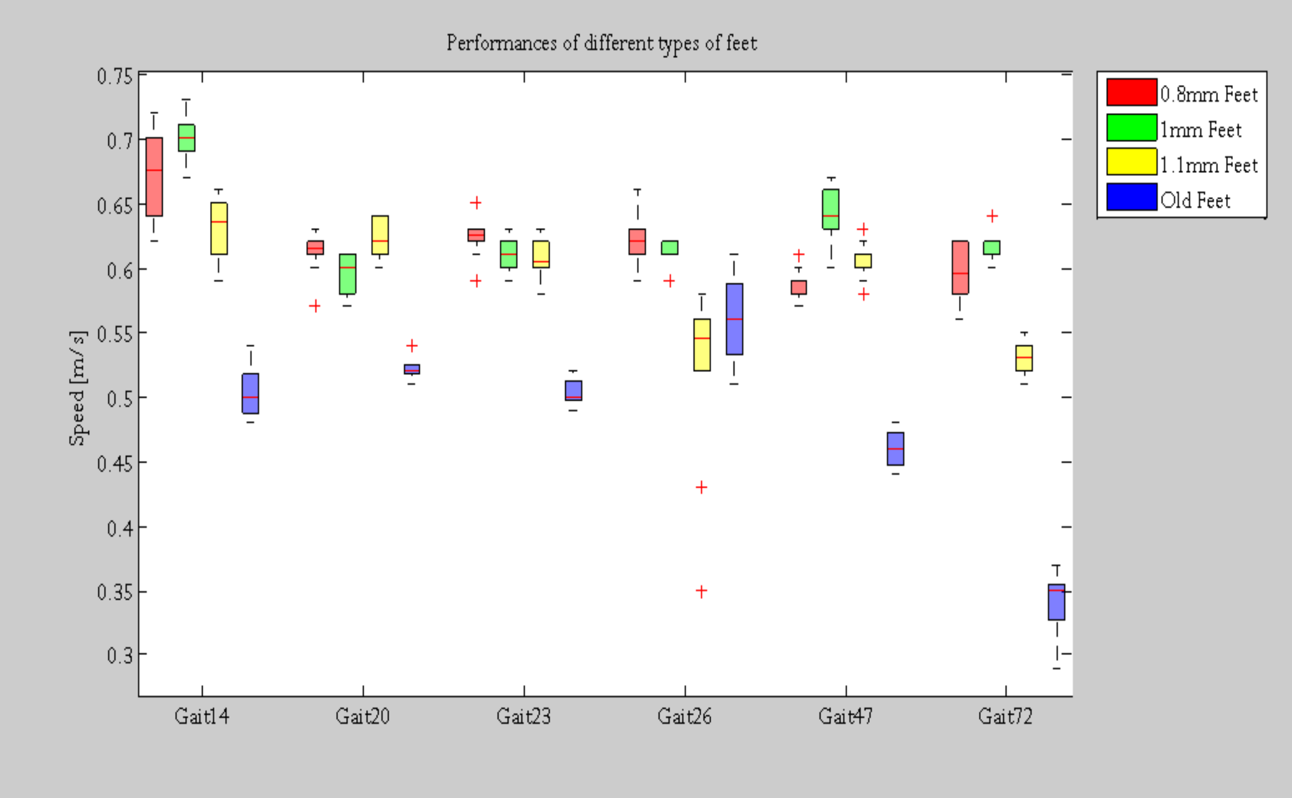


***Figure 13** Performances of the feet in terms of speeds. The results achieved with the 6 fastest gaits are shown. The outliers datas are shown as red crosses. The red bar is the median and the top and bottom of the bottom the 1st and 3rd quartiles respectively.*

Even if we assume that all this configurations are very similar in term of distribution, we can observe slight differences in certain gait. Figure 13 shows the results obtained with the four types of feet, including the old design that does not have necessarily a common distribution over the best gait. Firstly, we can observe that the new design is always significantly better than the old version of the feet. The only exception stands in gait *26*, were the *1.1mm* thick design have almost the same mean(0.52 . Moreover, some new speed record are reached with less stiff flexible joints, in gait *14* (*0.72m/s*). The maximum amelioration can be observed between old feet and *1mm* thick feet, in gait *72*, with an improvement of *77%* of the speed. We can moreover see that, while the results of the new design keep stable across the gaits, the performances of the old tend to decrease in gait *47* and *72* with *~ 0.45m/s* and *~ 0.35 m/s* in mean. Gait *20, 23* and *26* have very close results (no difference in statistical term, since there interval are joint) for *1mm* and *0.8mm* feet, with *0.62m/s* and *0.6m/s* in means, whereas the *1.1mm* shows a net degradation of the results that are significantly different than the two others. Regarding the outliers data in this column, we suppose that a changing in experiment conditions (friction, voltage level) occurred during these tests. Gait *14*, *47* and *72* show their best results using the *1mm* feet.

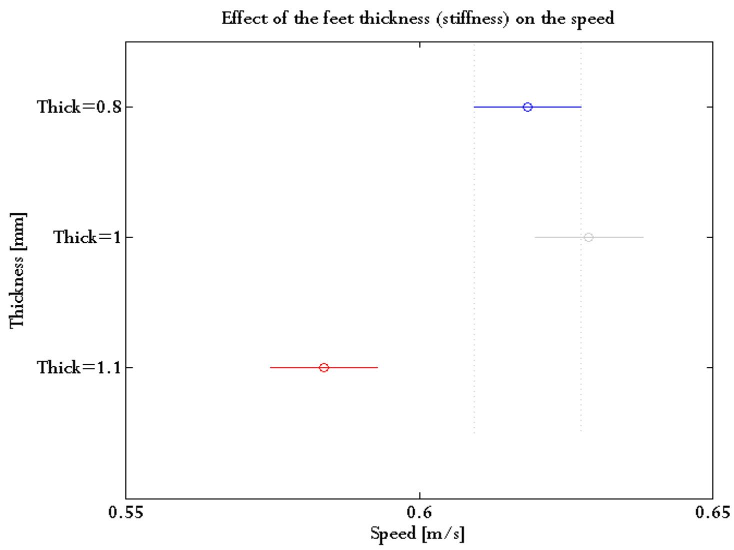


Figure 14 *Effect of the stiffness of toe joint on the speed distribution. The unjoint interval indicate a significant diffrence in mean.*

The F-Value of the thickness effect on the speed distribution is $5.7x10^{-8}$, the effect of this variable is therefore significant on the speed. In Figure 14, we consider assumption 1. The thickness effect on the speed in shown. Each thickness level contain 60 samples. We can observe that thickness *1.1mm* (*9Nm/°*) is clearly less good than the two other tested feet. With a mean speed of *0.58 m/s*, these feet are in average *10%* slower than the feet having a blade thickness of *1mm (5Nm/°) (0.62 m/s).*

4.2.4 Stability

The whole following analysis was done under assumption 1.The criterion use to assess the robots stability is based on the variations of amplitude of the difference in Z position of 2 opposite markers (eq. (6) (7))

Figure 15 *Plot of the Roll and Pitch signal after the mean filtering. Horizontal lines are the RMS values of this signals. We show the window between frame 0 and frame 400, on which the stability was assessed. This plot is arise of the gait 14 performed with the old version of the feet*

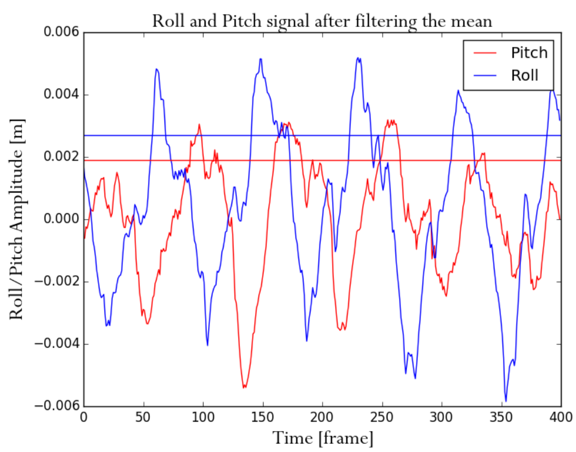


Figure 15 shows that the obtained signals after mean subtraction. They are effectively sinusoidal-like, the RMS value is therefore a good measure of their mean amplitude.

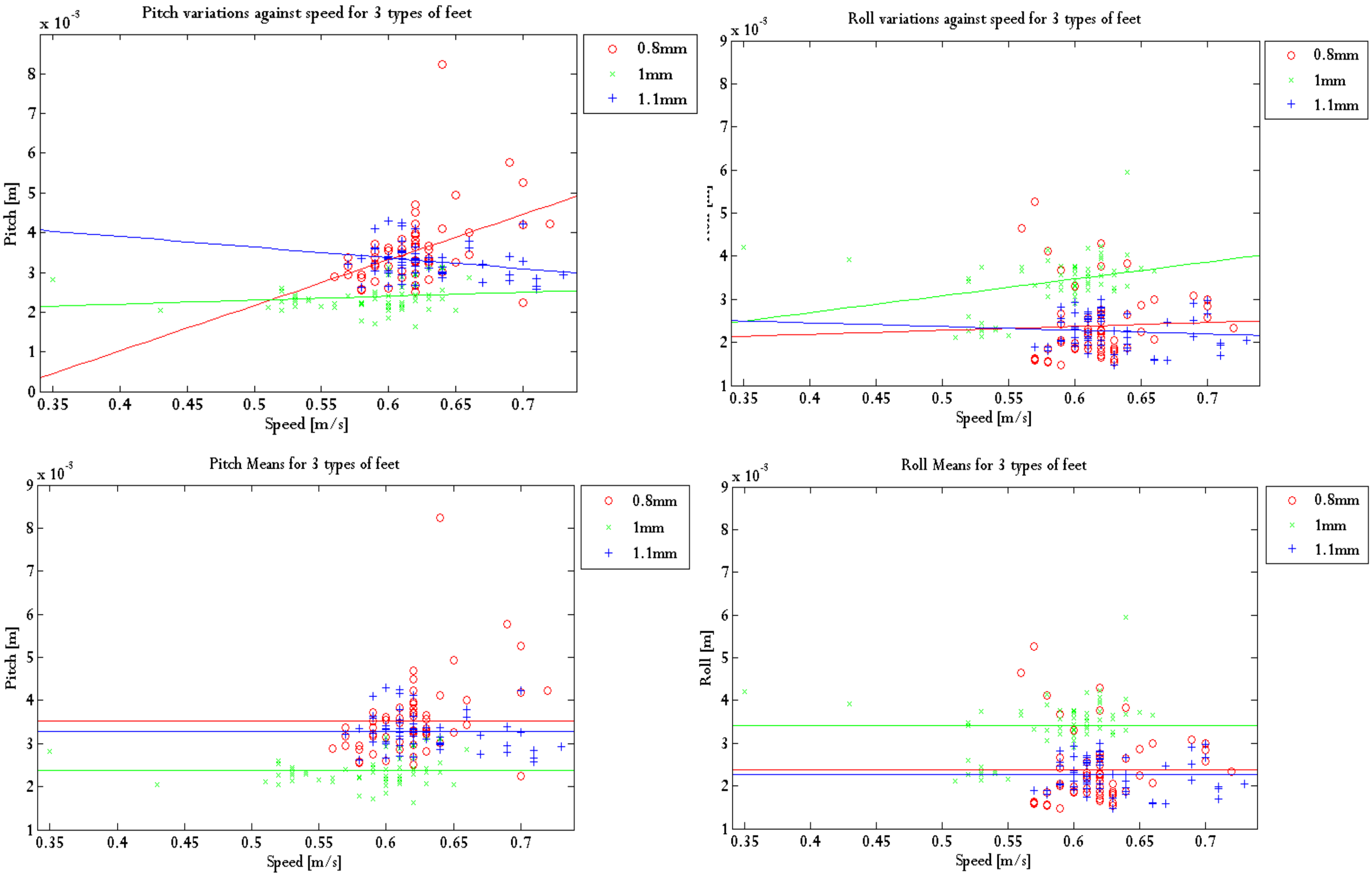


Figure 16 *Pitch/Roll amplitude variations against the speed of the robot. On top, the coloured lines are the 1st order linear fitted model on the data for each type of feet. On bottom, the horizontal lines are the mean of the pitch/roll population for given feet*

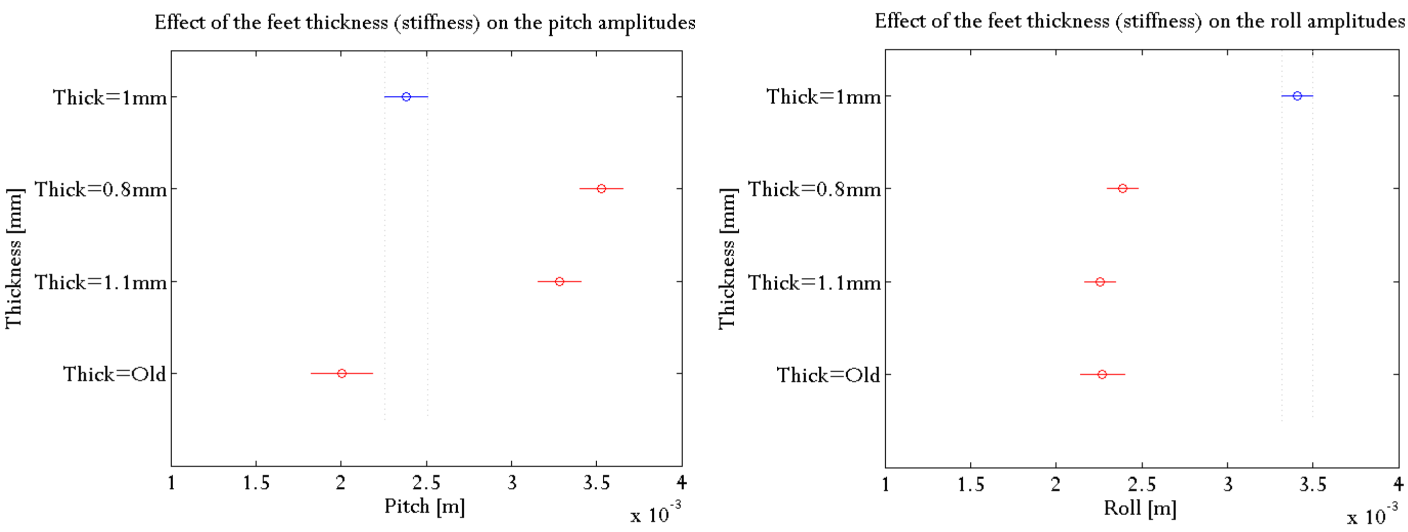


Figure 17 *Multi-comprison of the thickness and there effect on the pitch/roll mean amplitude*

In figure 16, we can see the pitch and roll (RMS values) for each thickness (stiffness) of the new design. Regarding the mean, the 1mm feet are better in term of pitch stability (2.4mm in mean) than the 2 others versions, but seem to induce a bigger roll instability (3.5mm). The 0.8mm and 1.1 mm show very close mean (3.5 mm and 3.2 mm for pitch, 2.2 mm and 2.5 mm on roll, respectively), but, Figure 17 tends to show that they are not significantly different and that they generate almost the same pitch/roll distribution. Even if the results of 1mm are better in term of pitch, they keep being significantly less good than the old version of the feet. On the other hand, 0.8 /1.1mm performances are equal to the old feet ones.

On the other hand, the linearly fitted model tend to show that the each stiffness is more adapted to particular range of speed. In term of pitch stability, the 0.8mm (stiffness) seem the potentially be adapted to speed smaller than 0.5m/s. From this point to speed up to 0.9 m/s, the 1mm thick feet (stiffness) could be more adapted. After this point, using a very stiff joint would lead a better stability than soft joints. Concerning the roll, we can see that the 0.8mm feet is again better adapted to small speed, leading to a better stability compared to the two other feet.

5 DISCUSSION

5.1.1 Design and Gait

Firstly, it is important to note that the tarasal-metatarsal joint was not assessed in this project. We noticed that letting this joint free to move caused dramatic gait. We think that it is due to the too low stiffness of the joint that we did not managed to rigidify, because time was missing. Moreover, the amplitude in which this joint could move was too big. As we design this by simple observation, the amplitude movement were note adapted to the sized of the robot. Moreover, only the negative (-15° in the case of this design) should be allowed. This changing in approach is motivated by the fact that we observed that blocking the positive flexion (what we practically did by locking the feet in backward position) lead to good gait. It could be interesting to test a new version of this joint showing a high stiffness (but still compliance) and a small amplitude range in which it could move. For example allowing a movement o. We do not want to give up this idea since this joint exists in real animals. The hypothesis that we made at the end of this project

The impossibility to test a correct trotting gait was disappointing. Even if we set the correct values of the phase lag, the controller seemed to always keep the same foot fall pattern that was almost a walking gait. It could be due to an overwriting of the set parameters in a hidden level of the controller to which we did not know. It could be necessary to check this kind of possible malfunction in the robot controller code. Another possibility is that some of the weights in the CPG controller have been changed, leading to this no satisfying gait. We did not have access to the CPG weights through the interface that we used, therefore we could not verify this assumption. This point should be also checked in further projects.

We hypothesized that achieving a correct trotting gait could improve even more the speed performances, since this kind of coordinated movement, in real biological system, are mostly used to achieve faster displacements.

5.1.2 Speed

The 6 chosen best gait were not the only ones that achieve such speed (0.61m/s in mean). Some other gait showing similar performances were not analysed. Regarding results obtained in 4.2.2, it is reasonable to think that all these gaits are arise from a single distribution determined by the hind offset. This parameter seems to be the determinant one. This observation is interesting. Knowing that in real digitigrade animals, most of the propulsion is provided by the hind limbs, this parameter should have a crucial importance, as well as the hind amplitude. We observed that this precise last parameter did not affect the speed. We hypothesized that it is due to the fact that we tested it in a range that was always bigger than the maximum amplitude necessary to propel the robot at full speed. Smaller value of this parameter should therefore be tested in order to assess correctly its effect on the robot speed.

We could achieve, at top speed, a linear displacement at 0.72m/s. Compared to the values obtain in first assessment of the Cheetah-Cub robot ([11]) using a 3Hz stride frequency and a supply voltage of 10V (between 0.6 m/s and 0.8 m/s),our value belongs to the same range of speed, without showing any improvement. But, in the other hands, we showed in this report that, using the same parameters with the old and new feet, we could achieve a real and important improvement with our design. The observed bettering could be due to the geometrical disposition of the flexible joints (since, we did not use the tarsal-metatarsal joint and that the heel did not really bent, the mechanical model is pretty the same as in ASLP model). The other possible source of amelioration could be the increased contact area due to the geometrical design of the feet. The adherence is increased this way and the propellant effect is then proportional.

We think that performing a deeper evaluation and tuning of the parameters of the CPG using the new feet, we could improve surpass the better performances of the well-tuned CPG with old feet. The potential improvement in the CPG could take place in a proper tuning of the stance deflection, since our design accumulate more energy than the previous one at the feet level, less energy is transmitted to the leg springs. It could be interesting to test this effects.

The fact that the robot does only move forward with a great coefficient of friction is an interesting property. It implies that if we can manage to set a high coefficient of friction of the feet on a slip surface that leads to a correct motion, the robot could probably walk on rougher terrain without problems, since it don't need the slippery effect to be propelled. It makes the robot robust against surface variations.

5.1.3 Stability

In stability results, some astonishing behaviour have been noted: The 0.8mm curve in pitch linear model seem to cross the horizontal axis before zero, leading to negative value of the pitch amplitudes. This may be caused be a too small set of data used in the fitting process. The roll amplitudes distribution due to the 0.8mm feet seem to be very wide (big variance), therefore, we think that more experiments should be performed in order to verify this fact.

The hypothesis that predicted an improvement of the stability due to the feet design have been reject. The results show that the independents toes are not responsible of a more stable posture of the robot body. But, interesting properties arose. It seems that the determinant factor is the stiffness of the toe joints during the gait. Within low speed gait, softer stiffness of the joint would lead to more stable posture whereas at high speed, the robot seems to need a higher stiffness. This behaviour can be related to the real biology. It is widely related that it exist in human, notably, a function that relate the speed to the joint stiffness, for the knee for example. It is therefore possible that cat or dogs achieve the same type of comportment at their toe joint. This result indicates the importance, in future work, to focus a part of the attention on developing selective stiffness mechanical joints, in order to achieve stable, rapid an fluent movements in robotics. The range in which this stiffness should vary is probably related to the size and mass of the robot of interest. Another part of the work should be to determine how does the stiffness vary among different mass population and speed and extract a systematic mean of design.

6 CONCLUSION AND FUTURE WORK

In this report a new feet design for the Cheetah-Cub robot was presented. Based on flexible joints, this design should be more energetically efficient than the previous versions of the feet. Moreover, due to its disjoint toe mechanics, the developed mechanical model should be more stable. We systematically tested the performances of these feet in a 81 runs grid search and in 210 statistical experiments, achieving good speed performances ($0.72m/s$) at top speed. We could moreover show the impact of the stride parameters (hind amplitude and offset, fore amplitude and offset) on the locomotion of this robot. We observed that the hind offset is mostly responsible of the variations in speed and should therefore be carefully chosen. The stiffness of the joint was also assessed in the speed performances. The results informed us on the importance of choosing correctly the stiffness of the joints when a specific speed range wants to be achieved. The best stiffness in the evaluated range was of almost **$5Nm/°$,** with the *1mm* thick feet. Some design principles arose in this project. The tarsal-metatarsal joint stiffness should be higher than ¼ of the toe stiffness and, moreover, should probably be bigger than this last value. Dramatic loss in performances were observed when we did not follow this specification. The stability of the robot is not due to the disjoint toes, but rather to the toe joint stiffness. This stiffness should be adapted in function of the speed and probably in function of the joint angle.

Further development could be investigate in the field of feet design. An interesting work could be done one the development of selective stiffness joints that could be useful not only in the feet structures but also in all actuated joints of a robot. It seems that this parameter is really decisive in fluent and dynamic gait since it has an influence on both speed and stability. Another research could look at a precise assessment of the tarsal-metatarsal joint properties and effect in robot locomotion.

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APPENDICES

APPENDIX I

At the very beginning of the project, some specifications have been establish in order to design a new interesting version of the feet. These specification were essentially qualitative and should be tested in the further experiments. The "to determine" notation should be filled after the project. Here is a list of these specifications that I made at the start of the project

Functions:

1) Accumulate and give back the energy
2) Guarantee sufficient stable contact with the ground
3) Avoid slipping of the robot
4) Improve locomotion by taking inspiration from the biological model
5) Should be contained in a similar volume then the previous version of the feet
6) Should be as light as the previous version of the feet
7) The paw should be compliant
8) The ankle should be compliant
9) The paw should be soft
10) The Toes should be soft
11) The feet should dissipate a minimum amount of energy during an entire stance phase
12) The energy should be given back by the feet as densely as possible.
13) The feet should be printable with actual 3D printing methods
14) The linkage between the l3 part of cheetah leg and the foot design should be reusable

Constraints	**Dimension**	**Value**	**Tolerance**
Should be contained in a volume of	mm^3	3700	+-300
Should have a maximum weight	g	8	+- 2
Should allow a maximum flexion between the paw and the toes under a force equivalent to 1.5 robot mass	°(degrees)	30	+- 5°
The paw should have a stiffness K_p of	N/m	To determine	
The ankle should have a stiffness K_a of	N/m	To determine	
The toe joint should have a stiffness K_t of	N/m	To determine	
The material used for the toes and paw should have a Young modulus smaller then	GPa		
The coefficient of friction between the ground and the feet should be bigger then	-	1	
The smallest resolution expected for the pieces should not be smaller the	mm	0.2	+-0.01

Solutions:

1) Use springs and reduce the friction. An interesting solution could be flexible joints. Another solution is a standard rotational joint, using bearing.
2) Flat ground contact of the feet. Area contact and not only line contact as it is actually the case.
3) Use of a caoutchouc layer on the bottom surface of the feet (use of 2 material printer?)
4) Look at important features in biological systems.

Conception:

According to this specification list I made two different models for the ankle joint and a single model of the feet. The two model of ankle joints were based on the two solutions proposed in 2). At the end I chose the use definitely the flexible solution because it was less costly and difficult to assemble then the bearing based ones. Since I wanted that the ankle was reusable, I made the feet and the ankle two pieces apart that can be slid one in the other. All the design was done with solidworks. I tried to keep as close as possible to the specifications when I was making the first prototype. At the end, the effective volume of the feet is $4200mm^3$, which is bit bigger than the limit that I fixed. But this choice was motivated by the fact that I needed space in order to create the flexible blades.

Materials **:**

The fabrication point was the more constraining part. The pieces should be printable by 3D printer, therefore the chosen material have to be adapted to this application. I should look at the available materials, such that I could create an adapted design with the flexure constraints and dimension.

3D printing at EPFL:

My interest was to have the best trade-off between the Tensile Strength, Flexural Stress and Elongation strength. After discussion with the responsible on the 3D printers at AFA Workshops, the choice of the 2 material 3D printer was forgotten because to difficult to print a flexible part using this technologie. An interesting alternative was the use of the SLS printer, that could both print some very thin pieces that was robust. After testing many exposition prototype, I chose to use this solution to build my pieces, based on my feeling. The used material is the PA 2200, that shows a 1700 MPa tensile modulus and a 1500 MPa Flexural modulus.

APPENDIX II

Grid search results table

fore amplitude	35																										
fore offset	-5									0									5								
hind amplitude	35			40			45			35			40			45			35			40			45		
hind offset	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5
file nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Fail			X			X			X		R1	X		R2	UN			UN			X		R3	X			X
Speed	0.35	0.56	0.37	0.31	0.47	0.46	0.31	0.48	0.45	0.46	0.58	0.43	0.5	0.63	0.48	0.46	0.58	0.54	0.54	0.64	0.45	0.46	0.61	0.54	0.45	0.61	0.61
Pitch	0.0017	0.0043	0.0043	0.0044	0.0028	0.0052	0.0040	0.0041	0.0056	0.0022	0.0029	0.0049	0.0030	0.0026	0.0048	0.0037	0.0036	0.0040	0.0024	0.0029	0.0080	0.0023	0.0028	0.0039	0.0032	0.0029	0.0047
Roll	0.002	0.002	0.003	0.003	0.003	0.027	0.003	0.0036	0.006	0.002	0.002	0.002	0.002	0.003	0.002	0.002	0.003	0.0033	0.002	0.002	0.036	0.003	0.004	0.004	0.004	0.004	0.01

fore amplitude	40																										
fore offset	-5									0									5								
hind amplitude	35			40			45			35			40			45			35			40			45		
hind offset	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5
file nr	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Fail		UN	X				X				*								X								
Speed	0.36	0.45	0.43	0.43	0.52	0.5	0.33	0.42	0.45	0.3	0.58	0.49	0.38	0.56	0.51	0.37	0.6	0.58	0.27	0.6	0.54	0.38	0.59	0.58	0.34	0.56	0.6
Pitch	0.0026	0.0027	0.0041	0.0038	0.0020	0.0035	0.0043	0.0036	0.0045	0.0025	0.0022	0.0040	0.0031	0.0021	0.0039	0.0035	0.0030	0.0044	0.0027	0.0021	0.0035	0.0032	0.0020	0.0034	0.0038	0.0025	0.0030
Roll	0.0025	0.004	0.003	0.003	0.003	0.002	0.002	0.003	0.005	0.004	0.003	0.002	0.003	0.003	0.006	0.003	0.004	0.007	0.004	0.003	0.004	0.003	0.004	0.005	0.004	0.003	0.006

fore amplitude	45																										
fore offset	-5									0									5								
hind amplitude	35			40			45			35			40			45			35			40			45		
hind offset	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5	-5	0	5
file nr	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
Fail	X																										
Speed	0.31	0.52	0.5	0.23	0.5	0.5	0.3	0.49	0.54	0.48	0.38	0.39	0.2	0.57	0.62	0.2	0.57	0.62	0.36	0.53	0.52	0.31	0.56	0.55	0.36	0.56	0.56
Pitch	0.0024	0.0031	Nan	0.0030	0.0040	0.0061	0.0032	0.0031	0.0038	0.0027	0.0024	0.0035	0.0051	0.0037	0.0034	0.0031	0.0039	0.0041	0.0036	0.0031	0.0043	0.0034	0.0035	0.0030	0.0041	0.0037	0.0041
Roll	0.003	0.003	Nan	0.003	0.003	0.004	0.004	0.003	0.003	0.002	0.002	0.004	0.004	0.003	0.003	0.004	0.003	0.004	0.003	0.002	0.003	0.003	0.003	0.003	0.004	0.003	0.003

Statistical Speed Results

Walk - Best Gaits - 1.1mm - Bending Stiffnes 0.5 mN/°								
	14	20	23	26	27	47	54	72
Tr1	0.59	0.61	0.6	0.35		0.63		0.53
Tr2	0.64	0.6	0.63	0.58		0.6		0.53
Tr3	0.59	0.6	0.6	0.43		0.59		0.51
Tr4	0.63	0.63	0.58	0.52		0.62		0.53
Tr5	0.62	0.62	0.6	0.53		0.6		0.54
Tr6	0.61	0.62	0.6	0.52		0.6		0.54
Tr7	0.65	0.61	0.62	0.56		0.61		0.53
Tr8	0.64	0.64	0.62	0.58		0.58		0.55
Tr9	0.66	0.64	0.61	0.56		0.6		0.52
Tr10	0.61	0.61	0.62	0.57		0.59		0.52
Max	0.66	0.64	0.63	0.58		0.63		0.55
Mean	0.62	0.62	0.61	0.52		0.60		0.53
STD	0.02	0.01	0.01	0.07		0.01		0.01

Walk - Best Gaits - 1mm - Bending Stiffnes 0.5 mN/°								
	14	20	23	26	27	47	54	72
Tr1	0.69	0.6	0.61	0.59		0.64		0.62
Tr2	0.69	0.59	0.61	0.61		0.6		0.6
Tr3	0.7	0.61	0.59	0.61		0.64		0.64
Tr4	0.69	0.61	0.62	0.62		0.67		0.61
Tr5	0.73	0.61	0.61	0.61		0.66		0.61
Tr6	0.71	0.6	0.63	0.62		0.64		0.6
Tr7	0.7	0.6	0.62	0.62		0.66		0.62
Tr8	0.71	0.58	0.59	0.59		0.64		0.62
Tr9	0.67	0.57	0.6	0.62		0.63		0.62
Tr10	0.71	0.58	0.61	0.61		0.63		0.64
Max	0.73	0.61	0.63	0.62		0.67		0.64
Mean	0.70	0.60	0.61	0.61		0.64		0.62
STD	0.02	0.01	0.01	0.01		0.02		0.01

Walk - Best Gaits - 0.8mm - Bending Stiffnes 0.5 mN/°								
	14	20	23	26	27	47	54	72
Tr1	0.69	0.61	0.59	0.59		0.57		0.59
Tr2	0.66	0.61	0.63	0.62		0.58		0.59
Tr3	0.72	0.57	0.63	0.62		0.58		0.62
Tr4	0.65	0.61	0.62	0.64		0.59		0.62
Tr5	0.64	0.6	0.63	0.62		0.61		0.62
Tr6	0.7	0.62	0.62	0.61		0.58		0.57
Tr7	0.7	0.63	0.61	0.62		0.6		0.56
Tr8	0.64	0.62	0.65	0.63		0.58		0.58
Tr9	0.62	0.62	0.62	0.66		0.59		0.6
Tr10	0.7	0.63	0.63	0.6		0.57		0.62
Max	0.72	0.63	0.65	0.66		0.61		0.62
Mean	0.67	0.61	0.62	0.62		0.59		0.60
STD	0.03	0.02	0.02	0.02		0.01		0.02

Walk - Best Old								
	14	20	23	26	27	47	54	72
Tr1	0.51	0.52	0.5	0.56		0.44		0.35
Tr2	0.5	0.52	0.52	0.58		0.46		0.29
Tr3	0.54	0.52	0.49	0.54		0.45		0.35
Tr4	0.48	0.51	0.51	0.51		0.47		0.37
Tr5	0.49	0.54	0.5	0.61		0.48		0.34
Max	0.54	0.54	0.52	0.61		0.48		0.37
Mean	0.50	0.52	0.50	0.56		0.46		0.34
STD	0.02	0.01	0.01	0.04		0.02		0.03

Statistical Pitch Results

Walk - Best Gaits - Pitch - 1mm						
	14	20	23	26	47	72
Tr1	0.002446	0.002887	0.002402	0.002827	0.002326	0.002436
Tr2	0.002551	0.003006	0.002063	0.002211	0.002245	0.002274
Tr3	0.002503	0.002105	0.002936	0.002044	0.002328	0.002105
Tr4	0.00311	0.002429	0.0022	0.002037	0.001632	0.002135
Tr5	0.002375	0.002427	0.003141	0.002392	0.002173	0.002292
Tr6	0.00212	0.002285	0.002399	0.002535	0.002035	0.002327
Tr7	0.002037	0.002632	0.00294	0.002209	0.002077	0.002311
Tr8	0.002328	0.003113	0.002968	0.001786	0.002229	0.00215
Tr9	0.002855	0.003132	0.002186	0.002115	0.001853	0.002274
Tr10	0.002243	0.00245	0.002672	0.002397	0.001714	0.002591
Max	0.003110	0.003132	0.003141	0.002827	0.002328	0.002591
Mean	0.002457	0.002647	0.002591	0.002255	0.002061	0.002290
STD	0.000326	0.000365	0.000389	0.000294	0.000251	0.000146

Walk - Best Gaits - Pitch 0.8						
	14	20	23	26	47	72
Tr1	0.005777	0.003837	0.003711	0.003516	0.00294	0.003375
Tr2	0.004009	0.003035	0.003659	0.003709	0.002946	0.002763
Tr3	0.004223	0.003166	0.003218	0.003927	0.002554	0.004702
Tr4	0.004937	0.003484	0.003635	0.003015	0.003204	0.004504
Tr5	0.004108	0.003147	0.003348	0.003816	0.00303	0.002682
Tr6	0.005264	0.002962	0.004218	0.003581	0.002576	0.002949
Tr7	0.004192	0.00329	0.002867	0.003301	0.003614	0.002883
Tr8	0.008249	0.003283	0.003261	0.003227	0.002856	0.002861
Tr9	0.003975	0.003715	0.003246	0.003439	0.003167	0.002592
Tr10	0.002243	0.002822	0.00357	0.003541	0.00337	0.002513
Max	0.008249	0.003837	0.004218	0.003927	0.003614	0.004702
Mean	0.004698	0.003274	0.003473	0.003507	0.003026	0.003182
STD	0.001564	0.000324	0.000369	0.000276	0.000331	0.000786

Walk - Best Gaits - Pitch 1.1mm						
	14	20	23	26	47	72
Tr1	0.00339	0.003038	0.003355	0.003628	0.003007	0.003353
Tr2	0.00295	0.003598	0.003543	0.004168	0.003318	0.002654
Tr3	0.004228	0.003111	0.003042	0.00317	0.002873	0.003
Tr4	0.002797	0.003795	0.002985	0.004111	0.002758	0.00325
Tr5	0.002935	0.003486	0.002706	0.003546	0.003782	0.002947
Tr6	0.002579	0.003404	0.003262	0.003316	0.00314	0.002994
Tr7	0.003269	0.004292	0.003167	0.00346	0.00362	0.002676
Tr8	0.00266	0.003345	0.003234	0.004102	0.002963	0.003261
Tr9	0.003198	0.003214	0.003354	0.003641	0.003097	0.003292
Tr10	0.002851	0.002621	0.004256	0.003521	0.003374	0.003367
Max	0.004228	0.004292	0.004256	0.004168	0.003782	0.003367
Mean	0.003086	0.003390	0.003290	0.003666	0.003193	0.003079
STD	0.000479	0.000454	0.000411	0.000348	0.000328	0.000267

Walk - Best Old Pitch						
	14	20	23	26	47	72
Tr1	0.002129	0.00118	0.001479	0.001819	0.001422	0.003967
Tr2	0.001525	0.000875	0.001148	0.001625	0.001635	0.003973
Tr3	0.001966	0.001264	0.001146	0.001618	0.001509	0.003635
Tr4	0.001719	0.001332	0.001422	0.004787	0.001609	0.003506
Tr5	0.001889	0.001354	0.001533	0.001574	0.001434	0.004105
Max	0.002129	0.001354	0.001533	0.004787	0.001635	0.004105
Mean	0.001846	0.001201	0.001346	0.002285	0.001522	0.003837
STD	0.000232	0.000194	0.000185	0.001402	0.000098	0.000254

Statistical Roll Results

Walk - Best Gaits - Roll- 1mm						
	14	20	23	26	47	72
Tr1	0.003775	0.003513	0.003321	0.004198	0.003185	0.002436
Tr2	0.003297	0.003774	0.003647	0.004139	0.00317	0.002274
Tr3	0.003346	0.003434	0.003597	0.003927	0.003561	0.002105
Tr4	0.003264	0.003576	0.003297	0.003424	0.00354	0.002135
Tr5	0.003358	0.004226	0.003702	0.003737	0.003059	0.002292
Tr6	0.003348	0.003953	0.003738	0.003477	0.002907	0.002327
Tr7	0.003712	0.003382	0.003743	0.003665	0.003211	0.002311
Tr8	0.003675	0.004023	0.004069	0.003892	0.003053	0.00215
Tr9	0.003649	0.005938	0.003706	0.003739	0.003304	0.002274
Tr10	0.003592	0.004184	0.00398	0.003334	0.00321	0.002591
Max	0.003775	0.005938	0.004069	0.004198	0.003561	0.002591
Mean	0.003502	0.004000	0.003680	0.003753	0.003220	0.002290
STD	0.000196	0.000746	0.000243	0.000292	0.000206	0.000146

Walk - Best Gaits - Roll 0.8						
	14	20	23	26	47	72
Tr1	0.003083	0.00231	0.002414	0.002008	0.001613	0.002666
Tr2	0.002999	0.001839	0.001874	0.002483	0.001565	0.003671
Tr3	0.002324	0.001624	0.00155	0.002111	0.001859	0.002645
Tr4	0.002857	0.002247	0.001988	0.00186	0.001464	0.002745
Tr5	0.002649	0.001839	0.001608	0.001778	0.001934	0.004284
Tr6	0.002579	0.00226	0.002205	0.002184	0.001544	0.005264
Tr7	0.002847	0.00179	0.002552	0.001861	0.001867	0.004647
Tr8	0.003831	0.001703	0.002236	0.002042	0.001553	0.004122
Tr9	0.002668	0.002288	0.001647	0.002071	0.002036	0.003294
Tr10	0.002996	0.001821	0.002037	0.001981	0.001579	0.003776
Max	0.003831	0.002310	0.002552	0.002483	0.002036	0.005264
Mean	0.002883	0.001972	0.002011	0.002038	0.001701	0.003711
STD	0.000405	0.000270	0.000345	0.000200	0.000201	0.000890

Walk - Best Gaits - Roll 1.1mm						
	14	20	23	26	47	72
Tr1	0.002141	0.002351	0.002136	0.002822	0.001796	0.003001
Tr2	0.002503	0.002556	0.002056	0.002496	0.001916	0.002115
Tr3	0.00267	0.001733	0.002042	0.002661	0.002105	0.002259
Tr4	0.002898	0.001931	0.002496	0.002635	0.001576	0.002608
Tr5	0.002044	0.002544	0.002094	0.002542	0.00161	0.00271
Tr6	0.001971	0.001974	0.002261	0.002789	0.001957	0.002679
Tr7	0.002977	0.002931	0.002049	0.002718	0.001594	0.001934
Tr8	0.001705	0.001895	0.002034	0.002459	0.001872	0.002619
Tr9	0.002474	0.001889	0.002309	0.002555	0.001725	0.002816
Tr10	0.001935	0.001798	0.002225	0.002133	0.001482	0.002662
Max	0.002977	0.002931	0.002496	0.002822	0.002105	0.003001
Mean	0.002332	0.002160	0.002170	0.002581	0.001763	0.002540
STD	0.000435	0.000405	0.000151	0.000198	0.000200	0.000332

Walk - Best Old Roll						
	14	20	23	26	47	72
Tr1	0.00266	0.001332	0.001681	0.00323	0.001151	0.003238
Tr2	0.002716	0.001244	0.001673	0.003246	0.001257	0.003347
Tr3	0.00279	0.001404	0.001538	0.002653	0.001222	0.003159
Tr4	0.00255	0.001267	0.001938	0.005103	0.001328	0.002806
Tr5	0.002696	0.001486	0.001428	0.003204	0.001168	0.003637
Max	0.002790	0.001486	0.001938	0.005103	0.001328	0.003637
Mean	0.002682	0.001347	0.001652	0.003487	0.001225	0.003237
STD	0.000088	0.000100	0.000191	0.000937	0.000071	0.000302