In Proceedings of 8th Workshop on Humanoid Soccer Robots
13th IEEE-RAS International Conference on Humanoid Robots (Humanoids), Atlanta, GA, 2013.

Current Usage Reduction Through Stiffness Control in Humanoid Robot

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***Abstract* — In this study the current usage of each associated joint of a humanoid robot (NAO) during stand up process is analyzed. This study is the extension of our previous study [1] where the energy consumption of single and overall joints of a NAO robot during the walking process was researched while keeping the same stiffness values for all joints. This paper analyzes current stiffness relation of individual joints and effects of variable stiffness values of each joint during standing up. A simple algorithm to find desired current usage hence stiffness value for each joint is presented. Different stiffness values for each joint are adapted individually during a simple standing up process according to drawn current.**

Keywords— humanoid robot, motor stiffness, motor control, energy analysis

I. INTRODUCTION

Robotics and especially the area related to humanoid robots have generated a great interest for researchers during the last decade. The latest research has advanced the study of mobility and balance, and it has developed techniques that allow the robot to walk in a manner similar to the human being. While advancing in this direction demonstrate very interesting challenges, one of the other challenges is related to the reduction of energy consumption. In some cases, this issue becomes the cornerstone of research demonstrating a fairly strong symbiosis between drawn current and robust control systems. This aspect can be seen in the context of the soccer humanoid league and Standard Platform League (SPL) of Robocup where the battery lasts a few minutes and it must be changed continuously affecting the performance of the robot during the game.

This work focuses on studying the effect of limiting the motor current during the stand-up process of a humanoid robot and developing a basic method for estimating current limit values in proportion to the overall current consumption. This work is inspired from research related with the low level of ankle joint stiffness during quiet standing [2], [3], as humans are expected to find a standing position where they can continue their normal tasks with low stiffness values.

In contrast with other works, we developed a basic method to find a stiffness limit in concordance to the full used current and performed a study of this developed method for the humanoid stand up process. In the study by Kulk and Welsh [4], [5], they studied the changes generated on the walking process after varying current limit values on a NAO Robot V3, where the results show an increase in the speed and reducing the consumption of energy by comparison of different optimization algorithms. In the study by Kormushev et al [6] the energy consumption is reduced by the application of reinforcement learning algorithm which caused a change in the height and center of mass of a COMAN humanoid robot during a walking process.

This paper is organized as follows. Section II describes basic concepts about stiffness and how it is used in the NAO humanoid platform. Section III explains the experimental setup. Section IV presents the method used to reduce drawn current. Section V shows the results of each experiment and analysis of results. Conclusions are drawn in section VI with comments.

II. FRAMEWORK

Stiffness control of individual joints is used directly to observe and to reach the desired level of used current. In order to make joints work, stiffness (hence power) is needed. In this paper, stiffness is described as current control mechanism for individual joints. Current applied is directly related to the stiffness control supplied to the joint hence torque is also directly related to the stiffness value. In NAO, this value can be set by the user for different tasks. Basically, the stiffness control function is sort of a limiting filter mechanism of current above certain level.

DC motor equations are well known [7], [8]. Torque of DC motor is directly related to current supplied, that is $\tau = k_\tau I$ where τ is electromagnetic torque, k_τ is the motor torque constant and I is the current supplied. This current is actually a controlled current, therefore current I, is written as $I = I_S K_S$ where I_s is the supplied current to the motor windings and K_S is the desired stiffness function for the joint. Motor voltage, current, and torque relations are:

$$\mathrm{V} = \mathrm{L}\frac{\mathrm{dI}}{\mathrm{dt}} + \mathrm{RI} + \mathrm{k_b w} \quad (1)$$

$$\tau - \mathrm{T_r} - \mathrm{T_L} = 0 \quad (2)$$

$$\mathrm{T_r} = \mathrm{J}\frac{\mathrm{d}}{\mathrm{dt}}\mathrm{w} \quad (3)$$

T_r is the torque due to rotational acceleration of the rotor, R is the motor winding resistance, k_b is the motor's back emf constant, and w is the rotor's angular velocity. J is the motor's moment of inertia, T_L is the load required torque by an external mechanical load.

After calculations and using Laplace transforms of the above equations gives:

$$\mathrm{I} = \frac{\mathrm{V} - \mathrm{k_b w}}{\mathrm{LS+R}} \tag{4}$$

$$\mathrm{w} = \frac{\mathrm{k_\tau I} - \mathrm{T_L}}{\mathrm{JS}} \tag{5}$$

$$\mathrm{I} = \frac{\mathrm{VJS} + \mathrm{k_b T_L} - \mathrm{k_b k_\tau I}}{\mathrm{JLS^2} + \mathrm{JRS}} \tag{6}$$

Above formula 6 shows the relation of applied current with the total inertia and voltage. The robot mass has a direct effect on almost all parts of robot tasks. Inertia directly is affected by changes in mass. Inertia can be observed in the varying resistance to motion of robot parts with different masses. Robot body joints are under different weight pressure even while the robot is standing. When the robot moves, its inertia of individual body parts and whole body increases. This is the reason that some joints are exposed to more Inertial forces during standing up tasks.

III. EXPERIMENTAL SETUP

We look at the individual joint level drawn current and stiffness current relation for NAO v3 and v4. That's why our study is contributing different results than other researchers [4], [5]. We also look at the stiffness, current and torque relation to influence the minimal current usage individually for each joints and overall in a humanoid.

In order to analyze the current usage of individual motors and overall current consumption, NAO version 3 and version 4 humanoid robots are tested for different tasks. Tasks included moving only one joint (such as Knee Pitch) in one direction under different stiffness values. Other task includes a simple stand up from a sitting position. Joints observed for current usage are Hip Pitch, Hip Roll, Hip Yaw Pitch, Knee Pitch, Ankle Pitch, and Ankle Roll. We used Python version 2.7 to program the robot and we made a new module in C++ to collect data from the robot, finally we use Matlab to analyze the data. NAO v4 used 1.14.1 and NAO v3 used 1.12.1 firmware at the time of tests. NAO v3 weighs 4.996 kg and v4 weighs 5.182 kg.

A. Individual Joint Current Usage Baseline Experiment

This experiment is designed to find the relation between stiffness coefficient and maximum drawn current allowed by this coefficient on each joint. This experiment is a baseline to find the new stiffness value in the second experiment. NAO v4 uses Athlonix brushed DC motor while NAO v3 uses Maxon DC motors [9]. Even though they are both DC motors, they demonstrate different current usage characteristics as expected.

In this test, a free joint movement with different stiffness values is conducted, and some weights to the same joint later are added (Fig. 1). Robot lifted its leg up as shown. The test used 3 same weights about 0.6 kg each. These weights were attached to the foot of the robot as shown. We started with only one weight (0.6 kg) completed a set of tests; later added the second one (1.2 kg) for another test and third one (1.8 kg) for the last test. The purpose was to find the maximum current that can be drawn by a single joint for each experiment without or with added weights to the joint. Same experiment was done five times for each stiffness value. Average data over these five experiments has been used to find the average current for that specific joint.

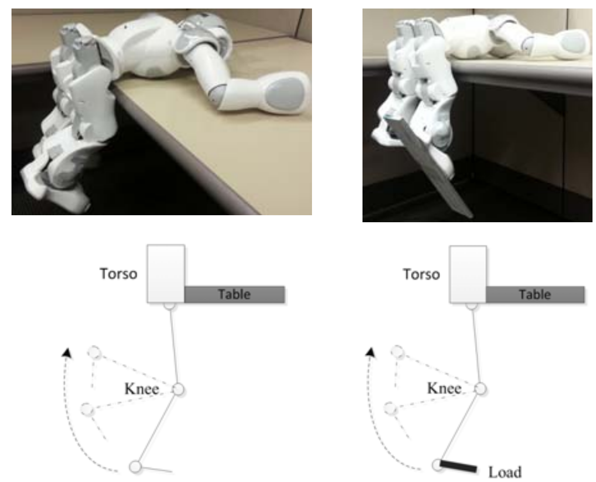

Fig. 1, Left pictures show free joint test setup and right pictures show joint test with a weight. Robot moves its leg up and down without a load and later with a load.

B. Standup Current Usage Experiment

The goal of this test is to reduce used current in a NAO during standing up process. The process is based on the search of minimum stiffness value so that the robot can stand up without falling. This stiffness value is different and it is related to the full current required for each joint. Robot start from crouch posture and goes to stand up posture as shown in Fig. 2.

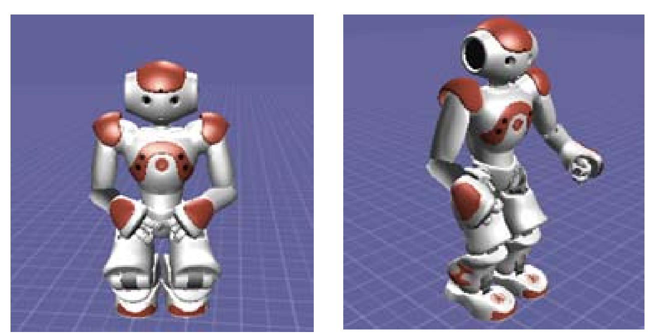

Fig. 2, Robot postures for the experiment, crouch position on the left picture, stand up posture on the right picture

IV. CURRENT ANALYSIS METHOD

This method is divided in two phases, the first one studies drawn current of robot with full current limit in every joint and the second method searches a stiffness value that allows reduced used current.

A. Measurement of full current drawn

For this phase of measurement, while the robot is standing up from a crouch position, current usage for each joint is collected for data processing. This phase has three steps as follows:

1-Data Acquisition: For each joint of the humanoid robot the stiffness value was set to 1.0 which allows full current drawing. Current withdrawn data is collected from each joint. Collected data is averaged over three different readings from each joint.

2-Histogram: Histogram of the data of previous step 1 is calculated to find out how common each sampled current value is during standing up process. The Fig. 3 shows the histogram of data acquired from knee pitch current sensor with a 10mA of resolution.

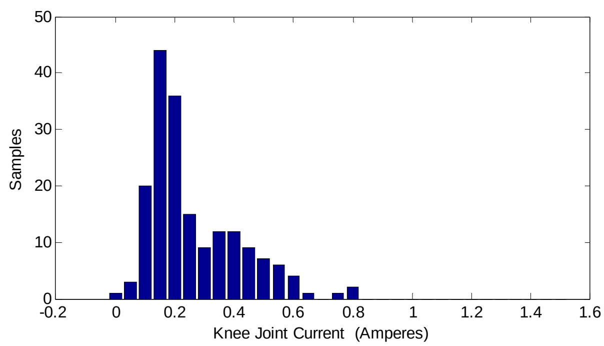

Fig. 3, Example Histogram of current data from ankle pitch joint for both single joint experiment and joint current usage experiments

3-Cumulative histogram: Using the histogram evaluated in the previous step 2, the cumulative histogram is calculated to provide the information about how the used current in the joint is related to the increasing of current. With this graph it is possible to analyze that 80% of total drawn current is less than 650mA (Fig. 4).

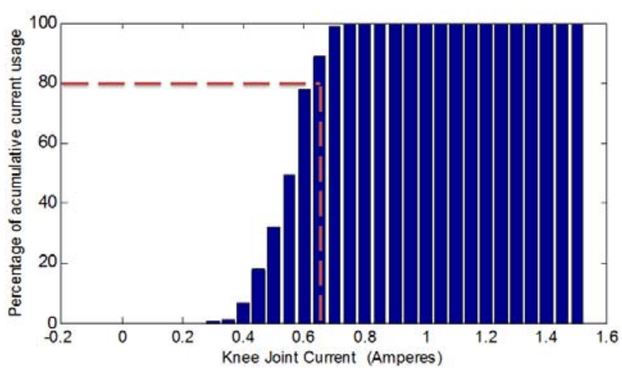

Fig. 4, – Cumulative Histogram shows which is the current required limit to reduce a specific percent of drawn current

B. Searching of Minimum Current for each joints

In this phase, a new stiffness value, which is expected to decrease the current usage is calculated. This part has three steps as following:

1-Determination of the desired drawn current value: The new expected current usage percentage is determined. The current usage percentage is a portion of cumulative drawn current, although it is used same factor, the final current limit will be different for each joint because every joint has different values of drawn current. It is necessary to be careful with this selection, because in some cases selecting a low value makes it impossible for the robot to continue standing up and results in robot fall. In that case, it is required to start with a new desired current usage percentage different than the last value used. This method does not ensure the stability of the robot, so it is necessary to return to this step and select a new percentage value to find one that would reduce drawn current and make robot stand up. This is not an automated process of stiffness reduction, it is adjusted manually.

2-Find the maximum current: The maximum current is found according to the percentage value selected in the last step. The cumulative histogram graph is used where percentage value is located along the y axis. The current is found at intersection of this percentage value and the current bar that has maximum value along x axis as is shown in Fig. 4. It is possible to see the relation of 650 mA and 80% of total accumulated used current in the figure.

3-Find stiffness value: Using the relation between stiffness and current, the new stiffness value is calculated according to the current limit which depends on percentage value selected. New stiffness values for NAO v3 is Current/1.5 and for NAO v4 it is Current/1.8. 1.5 and 1.8 are the maximum current for each robots DC motor.

This stiffness which is calculated with the same percentage value is applied to each joint. Each joint is tested with the same stiffness value five times, and the average of the five tests is taken to produce the new drawn current. The flowchart in Fig. 5 shows the process of selection of a new stiffness value.

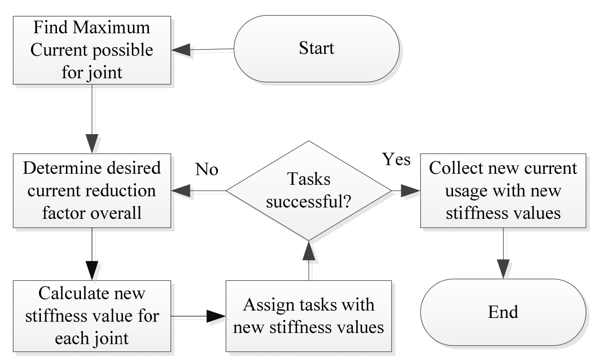

Fig. 5, Flowchart of the decision making for minimal current usage for stand up task

V. RESULTS AND ANALYSIS

In this section results for both experiments will be presented. First section shows the individual joint experiment results for current response and second section shows the standing up current study results and analysis.

A .Results from Individual Joint Current Experimental Results

Individual joint experiments show current limits for both versions of NAO robot. Depending on the load attached to the joint and stiffness value desired, current has been controlled. Current always has an upper boundary limit as seen in the following graphs.

Two cases are presented; the first one is when the value of stiffness is set to the maximum value which allows sufficient current to the motor for movement. In the second case, an extra weight is attached under the foot and a low stiffness value is used. This low current supplied to the motor is not enough to achieve the motion.

The two cases can be seen in Fig. 6, 7, 8 and 9. Fig. 6 shows the first case where the stiffness is set to 1.0 and the leg has no additional load, in this case the movement is complete and the current varies according to the movement, whereas the angle of rotation increases so does the consumed current. Fig. 7 shows the case where a weight of 1.2 kg is used with a stiffness value of 0.4, in this case the robot cannot make full motion because the current is limited at 600mA.

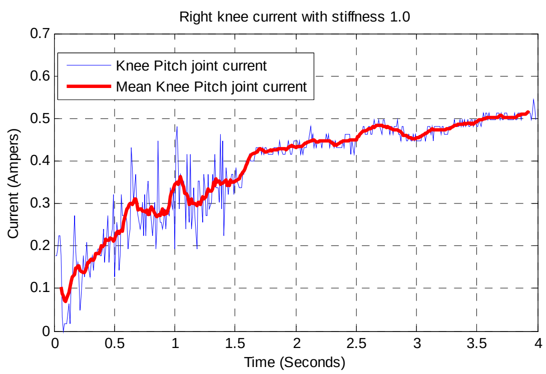

Fig. 6, for NAO v3, graph shows the current usage for free joint movement, max current is around 0.5A. No extra load is attached; Knee Pitch joint uses its own leg weight to do the test

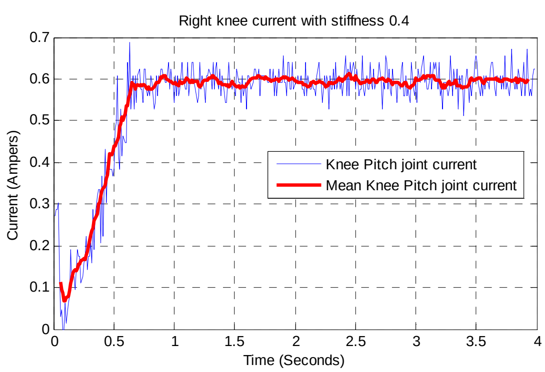

Fig. 7, NAO v3 single joint current response with extra load of 1.2 Kg and stiffness 0.4, the current is limited at 600 mA

Following the experiment, a weight of 1.2 Kg was added and the test was repeated for stiffness values between 0 and 1 with increments of 0.05. This test generated Fig. 8 which shows that for stiffness values lower than 0.6 the movement was not completed. The graph shows the maximum allowable current. For stiffness values above 0.6, current remains constant because the current required for movement is adequate and stiffness value is over the marginal value of the current. Fig. 9 shows the current usage of NAO v4 with weight attached to the knee joint.

Finally, the previous experiment was repeated with extra loads of 0.6 Kg, 1.2 Kg and 1.8 Kg with results shown in Fig. 10 and 11. The obtained curves are observed for each of the weights including 0 Kg (no additional weight added). It can be concluded from the results that as the weight is increased it is necessary to adjust the stiffness to higher values in order to perform a stable movement. It is also observed that with the weight of 1.8 kg it was never possible to make the full movement. Fig. 11 shows all current values for each limit values of stiffness.

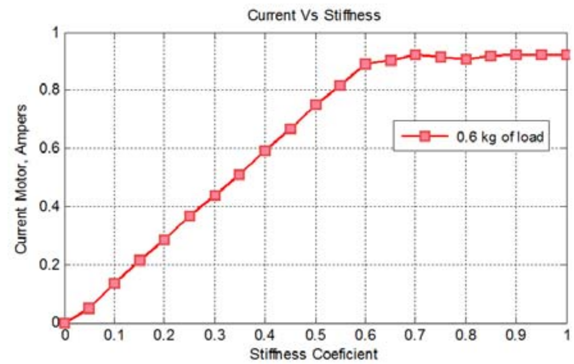

Fig. 8, NAO v3 Knee Joint current response to an extra weight attached to the foot.

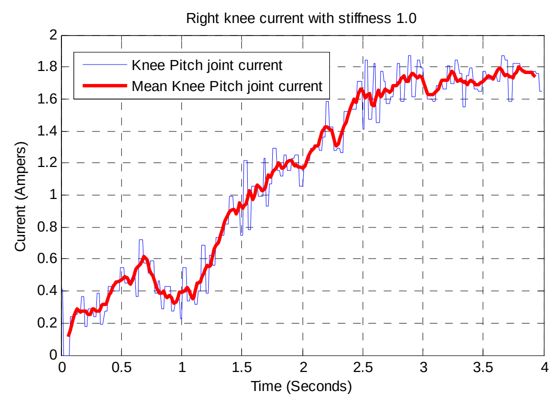

Fig. 9, NAO v4 Knee Pitch joint current response to a load, max current is about 1.8 A.

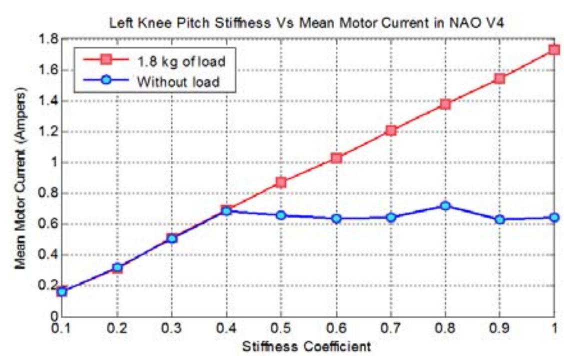

Fig. 10, for NAO v4, Knee pitch joint current response for free joint move (red) and current-stiffness relation for the same joint weight attached to it (blue). Blue line shows linear response with increasing stiffness and increasing weight input for the joint whereas red line shows maximum 0.6 A even with maximum stiffness values without any load.

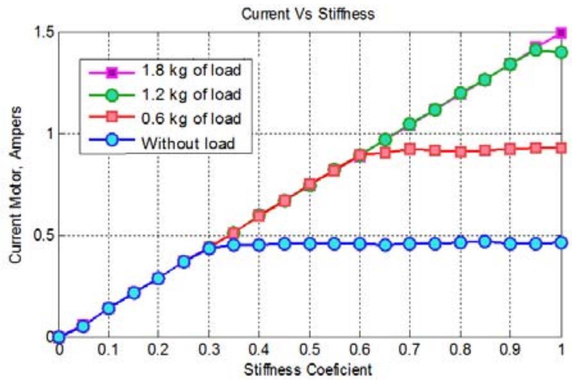

Fig. 11, This graph shows the stiffness and current usage relation for no-load and with three different loads for NAO v3 knee joint.

Fig. 10 and 11 show maximum current attainable with that DC motor. For free moving joints, maximum current is around 0.5 A for both NAO v3 and v4. Under load NAO v4 Athlonix DC motor is able to get almost 1.8 A (Fig. 10) while NAO v3 Maxon motor uses about 1.5 A.

For the conclusion from experiment in section A, the resulting relationship between the current limit and the value of stiffness is a straight line with slope where, in the NAO V3 slope value is 1.5 and, in NAO V4 slope value is 1.8. This expected behavior is noticeably observed in Fig. 10 and 11, where it forms a straight line with those characteristics.

B. Stand up-Sit down Current Usage Results

The method described above is applied to reduce the drawn power by applying a reduction factor during robot stand up without affecting the task. Tests were conducted on V3 and V4 robots using different current reduction ratio. Each test was performed 5 times and as a result the average reduced current in each of the joints and overall reduction in current consumption on the robot is obtained. Below tables show the comparison of total current usage with the new stiffness current. For Table I-IV, Expected Usage Factor represents a portion of full used current that is expected to use with the new stiffness value. Table I shows the comparison of total current usage with the new stiffness current that was calculated for reduction factor 0.84 overall for all joints for NAO v4.

TABLE I.

		Current Usage of each joint of NAO robot V4					
		Knee	**Ankle Roll**	**Ankle Pitch**	**Hip Pitch**	**Hip Roll**	**Hip Yaw**
Expected usage Factor	1	0.526	0.078	0.390	0.150	0.168	0.200
	0.95	0.579	0.098	0.309	0.127	0.168	0.176
	0.9	0.525	0.092	0.354	0.145	0.184	0.197
	0.84	0.562	0.070	0.385	0.106	0.167	0.141

NAO v4 Joint Current response comparison with full stiffness and new analyzed stiffness.

Results in Table II show different drawn current reduction ratios for each joint. While hip pitch joint has the biggest current saving, knee joint actually used more current with new calculated stiffness value. This increased current usage in knee joints needs further investigation. Every joint in the robot is under different weight stress during the standing up task. Knee joint is actually carrying most of robot weight. Even though ankle joints carry the whole robot weight, we do not see an increased current usage in them. The overall total current saving ratio is close to 11%.

TABLE II.

		Reduced Current Percentage %					
		Knee	**Ankle Roll**	**Ankle Pitch**	**Hip Pitch**	**Hip Roll**	**Hip Yaw**
Expected usage Factor	0.95	-9.9	-25.9	20.7	14.9	-0.2	12.1
	0.9	0.2	-18.5	9.1	3.2	-9.7	1.7
	0.84	-6.8	9	1.2	29.2	0.6	29.3

Percentage of current reduction for NAO V4

TABLE III.

		Current Usage of each joint of NAO robot V3					
		Knee	**Ankle Roll**	**Ankle Pitch**	**Hip Pitch**	**Hip Roll**	**Hip Yaw**
Expected usage Factor	1	0.526	0.176	0.366	0.159	0.117	0.176
	0.95	0.496	0.161	0.348	0.145	0.089	0.157
	0.9	0.525	0.176	0.322	0.113	0.105	0.151
	0.85	0.495	0.174	0.300	0.100	0.113	0.137
	0.8	0.445	0.167	0.309	0.107	0.099	0.135
	0.75	0.448	0.154	0.329	0.100	0.085	0.120

NAO v3, average current for each joint versus current reduction factor.

Table III shows that the average current in each joint decrease as does the reduction factor. The data with factor 1 is used as the total drawn current from which the percentage of current reduction value is calculated. These data are seen in Table IV which shows that factors Hip has larger reduction and ankles have minor percentage.

TABLE IV.

Reduced Current Percentage %							
		Reduced Current Percentage %					
		Knees	**Ankles Roll**	**Ankles Pitch**	**Hip Pitch**	**Hip Roll**	**Hip Yaw**
Expected usage Factor	0.95	5.7	8.52	4.92	8.81	23.93	10.8
	0.9	0.19	0	12.02	28.93	10.26	14.2
	0.85	5.89	1.14	18.03	37.11	3.42	22.16
	0.8	15.4	5.11	15.57	32.7	15.38	23.3
	0.75	14.83	12.5	10.11	37.11	27.35	31.82

Percentage of current reduction for NAO V3

Fig. 12 shows the total percentage reduction in each factor. It is observed that as factor increases, the reduction rate of current usage decreases. These data were obtained in the test at NAO V3 with minimum factor in 0.75. This was selected because with small factors it was impossible for the robot to stand up. For NAO robot V4 the same experiments were conducted to find that the minimum factor that could be used and the same time the robot can perform the task. It was 0.84, the current and reduction percentage data are shown in Table II.

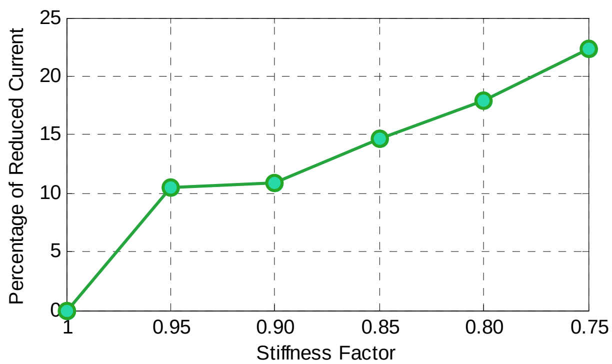

Fig. 12, Total Reduction percentage of current consumption

Fig. -13 and 14 show the effect of current reduction in time. Blue signal is the current of knee joint with factor 1.0 and the red one is the same signal with factor of 0.75 for the NAO V3 and 0.84 for V4. It is seen in both graphs that the current is limited by the factor being used and the difference between blue and red signal gives an idea of how it is performing the reduction of used current.

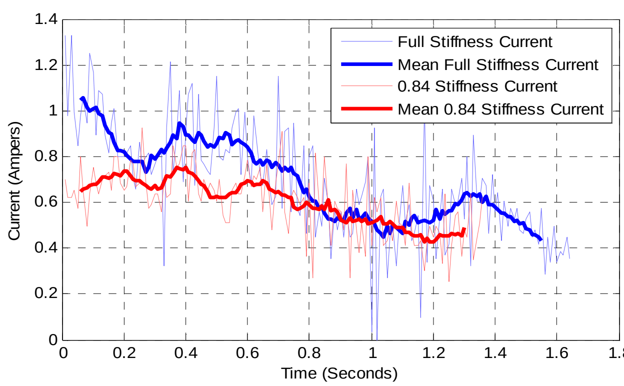

Fig. 13, Knee pitch joints current response of standing up for stiffness 1 (blue) and new stiffness applied (red)

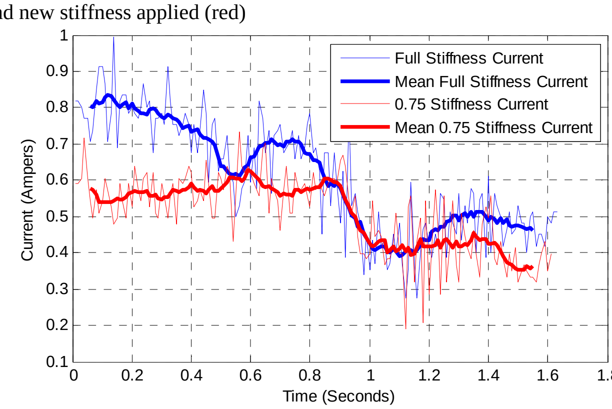

Fig. 14 - Knee Current response to full stiffness and 0.75 stiffness

VI. CONCLUSION

In this research, the drawn current of each Hip Pitch, Hip Roll, Hip Yaw Pitch, Knee Pitch, Ankle Pitch, and Ankle Roll joints during stand up process for NAO version 3 and version 4 was analyzed. This study showed current stiffness relation of an individual joint and effects of extra weight. Different stiffness values for each joint are adapted individually during a stand up process according to drawn current. Following this proposed method a new stiffness value can be calculated to reduce current withdrawn in a proportional way for each joint while the robot can continue perform normal process; in this case the process was to make the robot stand up. A considerable reduction of current is achieved. In the future this method can be utilized in other process such as walking. Relation between mass, inertia, current usage, stiffness and location of each joint needs to be analyzed further in order to ensure the complete understanding of different current usage for each joints during different tasks.

ACKNOWLEDGEMENTS

This work has been funded in part by NSF IIS Robust Intelligence research grant #1117303 at USF entitled “Investigations of the Role of Dorsal versus Ventral Place and Grid Cells during Multi-Scale Spatial Navigation in Rats and Robots.” We thank Martin Llofriu at USF for his help with the experimental software.

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