Optimizing Energy Usage through Variable Joint Stiffness Control during Humanoid Robot Walking

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Abstract. The objective of this paper and our current research is to optimize energy usage in a humanoid robot during diverse tasks such as basic walking by dynamically controlling individual joint stiffness. In the current work we analyze individual and total usage of current, voltage and power in a NAO V4 humanoid robot joints during short walks around a circle at different speeds and under varying control of joint stiffness. We perform experimental studies to understand the main factors affecting power consumption and energy usage and look at ways to improve overall energy usage. We describe experiments and corresponding results. We discuss the state of advancement of our research.

Keywords: Energy usage, power consumption, joint stiffness, motor control, humanoid robots.

1 Introduction

A critical challenge in mobile robots is the optimization of energy usage during specific robot tasks [1-3]. This is particularly relevant to humanoid robots where the increased number of joints and corresponding DOFs make energy usage hard to analyze and optimize during basic tasks such as walking [4]. In general, battery life is one of the main constraints in the use of robots for extended time. In the context of RoboCup soccer, games last only a few minutes where batteries are usually recharged at half time. As battery usage improves we expect future games to last longer or have power restrictions imposed on teams.

As part of our goal to better understand energy usage in robots and develop appropriate energy optimization algorithms, we present in this paper our initial study on power consumption in the NAO V4 humanoid robot in the context of the Standard Platform League (SPL). We analyze current, voltage and power consumption at individual joints and improve their usage by dynamically modifying motor stiffness without sacrificing task performance. We analyze the effect of variations on walking step frequency and joint stiffness on overall energy usage during simple short walks.

In contrast to other work we develop more in depth analysis of power consumption and energy usage in both individual joint and overall system at various speeds. In the

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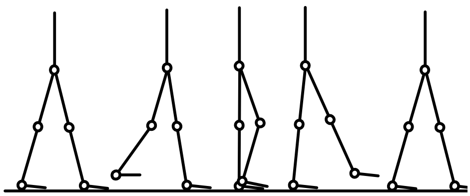
study by Kormushev et al. [5] electric energy consumption is optimized on the COMAN humanoid robot during walking by varying-height and robot's center of mass. The authors applied reinforcement learning algorithm to reduce the energy utilization with respect to variations in the robot's center of mass position. In the study by Kulk and Welsh [6-8], the authors compare various optimization algorithms to reduce overall energy usage while increasing walking speed. The authors analyze energy usage in an older NAO V3 by reading current from joints and voltage and analyzing primarily overall power usage in the system.

In the rest of the paper we briefly discuss in Section 2 the humanoid biped walking in the NAO that will be used for our experiments; in Section 3 we describe the basis for the power consumption and energy usage analysis; in Section 4 we describe the experimental results; and we finish by conclusions where we discuss our findings and future work.

2 Humanoid Robot Walking

While there are numerous approaches to humanoid robot biped walking, we will concentrate in this paper on the NAO open-loop walk engine [9]. The NAO V4 robot includes 25 degrees of freedom (DOF) including five DOF in each leg (3 in the hip, 1 in the knee, and 2 in the ankle) each controlled by a brushed DC motor with magnetic rotary encoders for position feedback. The NAO walk patterns are generated from a Zero-Moment Point (ZMP) [10] trajectory that is calculated from user specified step parameters that include walking step frequency, walking step width and walking step length. The ZMP trajectory is transformed into a center of gravity (CoG) trajectory using an inverted pendulum model [11-12].



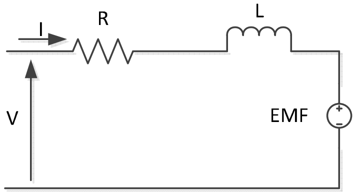


Fig. 1. (Left) Diagram illustrating the humanoid robot joints side connectivity schematics (hip pitch, knee pitch and ankle pitch). (Right) Magnetic brush DC motor used in and equivalent circuitry for the NAO DC motors with EMF representing the Electro-Magnetic Force [13].

3 Energy Usage during Humanoid Robot Walking

The energy usage of the humanoid robot joints can be computed from the corresponding motors controlling each joint. Figure 2 (left) shows the electrical circuit, while (middle) shows the corresponding joint location in the NAO V4, and (right) shows the joint connectivity schematics. To compute full energy usage in the system additional components in the robot need to be considered including CPU, sensors, communications, etc. Note that the NAO uses different types of motors depending on version and joint location [14]. To compute the energy usage of each motor in the robot we need to first compute power defined by motor voltage and current. In the following equations we describe the basic equations defining motor power and energy usage [15].

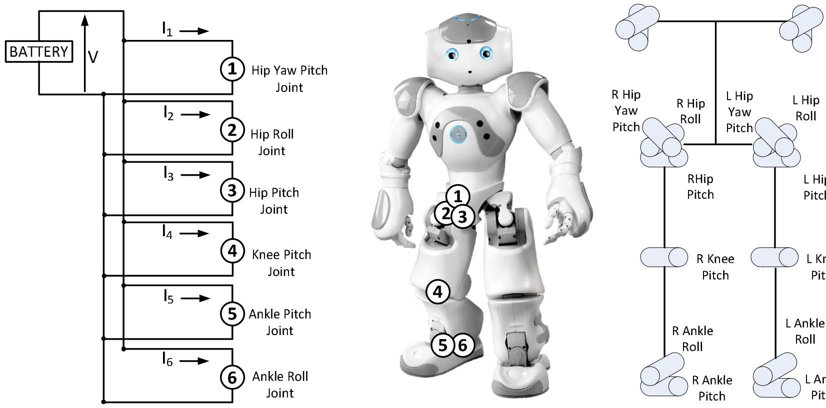


Fig. 2. (Left) Electric diagram of lower body NAO joints: Hip Yaw Pitch, Hip Pitch, Hip Roll, Knee Pitch, Ankle Pitch, Ankle Roll. (Middle) Corresponding location of joints in NAO robot. (Right) Diagram showing joints relative location.

In Eq (1), voltage V is equal to the change in motor inductance L, the current I through the motor windings with resistance R, and the motor torque constant k_b corresponding to the motor's back-EMF multiplied by the motor's rotor angular velocity $\dot{\theta}$,

$$V = L\frac{dI}{dt} + RI + k_b\dot{\theta} \tag{1}$$

In Eq (2), the motor's moment of inertia M multiplied by the robot's acceleration $\ddot{\theta}$ is equivalent to the motor's torque constant k_t multiplied by the electric current minus the motor's viscous friction constant ν times motor angular speed minus the torque τ being applied from the external load,

$$M\ddot{\theta} = k_t I - \nu\dot{\theta} - \tau \tag{2}$$

At steady state the voltage V and torque τ are given by Eqs (3-7)

$$V = RI + k_b\dot{\theta} \tag{3}$$

$$\tau = k_t I - \nu\dot{\theta} \tag{4}$$

$$V = \tau\frac{R}{k_t} + \frac{R\nu\dot{\theta}}{k_t} + k_b\dot{\theta} \tag{5}$$

$$\dot{\theta} = \left(\nu + \frac{k_b k_t}{R}\right)^{-1}\left(V\frac{k_t}{R} - \tau\right) \tag{6}$$

$$\tau = V\frac{k_t}{R} - \left(\nu + \frac{k_b k_t}{R}\right)\dot{\theta} \tag{7}$$

Stall torque τ_s at zero angular velocity is given when $\dot{\theta} = 0$ as shown by Eq (8)

$$\tau_s = V\frac{k_t}{R} \tag{8}$$

And the corresponding stall current I_s is given by Eq (9)

$$I_s = \frac{\tau_s}{k_t} = \frac{V}{R} \tag{9}$$

As current increases in the joint, torque also increases until it gets to a maximum level, i.e. the stall torque. The "no load" max speed $\dot{\theta}_n$ is defined when torque $\tau = 0$ given by Eq (10)

$$\dot{\theta}_n = \tau_s\left(\nu + \frac{k_b k_t}{R}\right)^{-1} \tag{10}$$

At steady state, the motor angular velocity $\dot{\theta}$, the torque τ and current I_s can be defined by Eqs (11-13),

$$\dot{\theta} = \dot{\theta}_n - \left(\nu + \frac{k_b k_t}{R}\right)^{-1}\tau \tag{11}$$

$$\tau = \tau_s - \left(\nu + \frac{k_b k_t}{R}\right)\dot{\theta} \tag{12}$$

$$I = I_s - \left(\frac{\nu}{k_t} + \frac{k_b}{R}\right)\dot{\theta} \tag{13}$$

Mechanical power P delivered by the motor is given by multiplying torque by motor angular velocity as shown by Eq (14)

$$P = \tau\dot{\theta} = \tau_s\dot{\theta} - \left(\nu + \frac{k_b k_t}{R}\right)\dot{\theta}^2 \tag{14}$$

Total power consumption P_{total} at time t is the summation of power P_i from all joints where i denotes the i-th joint as given by Eq (15),

$$P_{total} = V\sum_{i=i}^{n} I_i = \sum_{i=i}^{n} P_i \tag{15}$$

Finally, energy usage integrates power in time as described by Eq (16)

$$E = \int P_{total}dt \tag{16}$$

4 Experimental Results

In order to analyze power consumption and energy usage in the NAO V4 humanoid robot, we developed a simple walking experiment where the robot walks counter-clockwise around a small circle having 1 meter in diameter. We read electric current and voltage data from individual joints while walking at different speeds for about 1.5 minutes corresponding to 4-5 circles at max walking speed. We collected during each experiment approximately 2000 sets of data for each joint under different values of stiffness, walking step length and walking step frequency for both left and right joints: Hip Yaw Pitch, Hip Roll, Hip Pitch, Knee Pitch, Ankle Pitch, Ankle Roll. Note that a single motor controls in the NAO both Left and Right Hip Yaw Pitch joints. We performed each experiment three times and produced individual joint averages from those runs. Due to slow readings from the NAO motor joints, individual joint data was read at each experiment with stiffness and walking parameters changed at different runs. For data reading we used the NAO SDK platform version 12.3 under Python version 2.7. Current and voltage data was collected and saved into a text file for offline analysis. The following section of code illustrates the portion used to collect the data:

```
ALMEMORY_KEY_NAMES = [ "Device/SubDeviceList/LAnklePitch/ElectricCurrent/Sensor/Value",
"Device/SubDeviceList/Battery/Charge/Sensor/CellVoltageMin",]

for key in ALMEMORY_KEY_NAMES:
        value = memory.getData(key)
```

Table 1 shows robot defaults and range of values used during the various experiments.

4.1 Hip Pitch Joint

Figures 3, 4, and 5 show Left Hip Pitch joint current, voltage and power for three stiffness values (1, 0.8 and 0.6) walking at maximum speed.

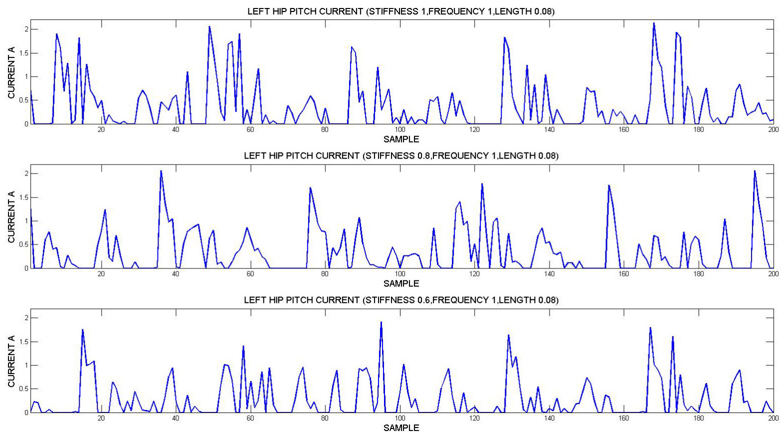


Fig. 3. Left Hip Pitch joint current usage at walking speed frequency 1 and step length 0.8 with the following stiffness (top) stiffness 1, (middle) stiffness 0.8, (bottom) stiffness 0.6

Table 1. The values to be changed during the experiment. Joint stiffness, walking step frequency and length were used as input to the humanoid system in order to obtain the output. Default values, their maximum and minimum values are presented in this table.

Name	Minimum	Maximum	Default
Joint Stiffness	0	1	1
Walking Step Frequency	0 (1.667 Hz)	1 (2.382 Hz)	1
Walking Step Length	0.001 (m)	0.08 (m)	0.04 (m)

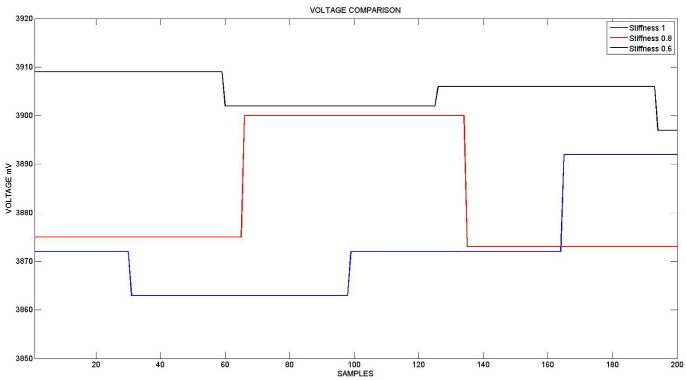


Fig. 4. Battery voltage usage for various Left Hip Pitch joint stiffness at walking speed frequency 1 and step length 0.8: (black) stiffness 1, (red) stiffness 0.8, (blue) stiffness 0.6.

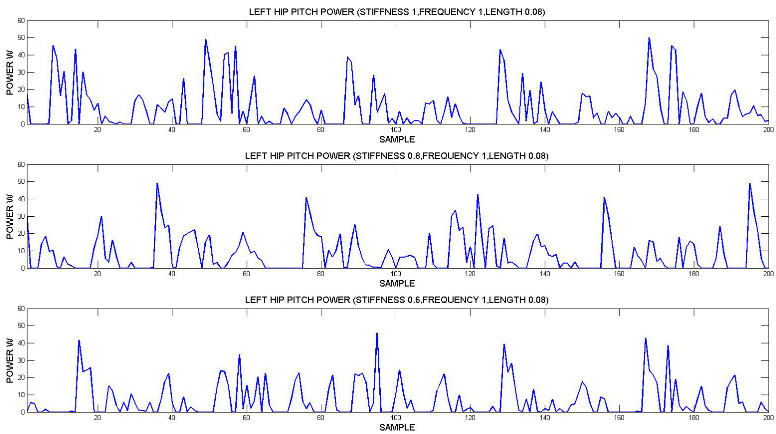


Fig. 5. Left Hip Pitch joint power usage at walking speed frequency 1 and step length 0.8 with the following stiffness (top) stiffness 1, (middle) stiffness 0.8, (bottom) stiffness 0.6.

4.2 Knee Pitch Joint

Figures 6, 7, and 8 show Left Knee Pitch joint current, voltage and power for three stiffness values (1, 0.8 and 0.6) walking at maximum speed.

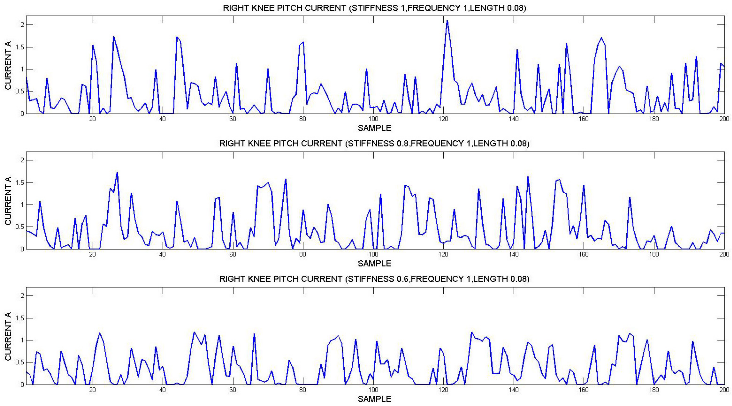


Fig. 6. Left Knee Pitch joint current usage at walking speed frequency 1 and step length 0.8 with the following stiffness (top) stiffness 1, (middle) stiffness 0.8, (bottom) stiffness 0.6

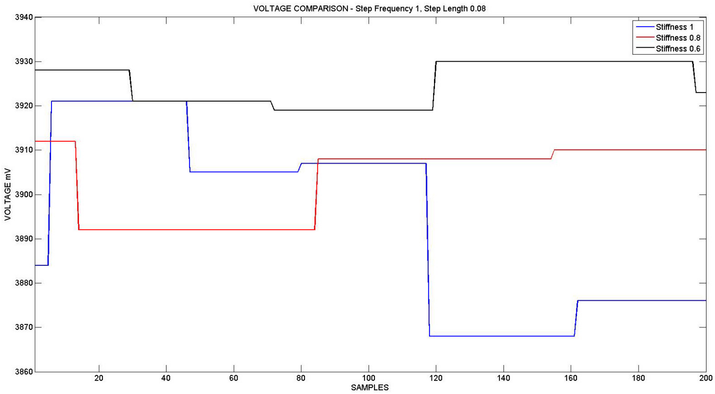


Fig. 7. Battery voltage usage for various Left Knee Pitch joint stiffness at walking speed frequency 1 and step length 0.8: (black) stiffness 0.6, (red) stiffness 0.8, (blue) stiffness 1

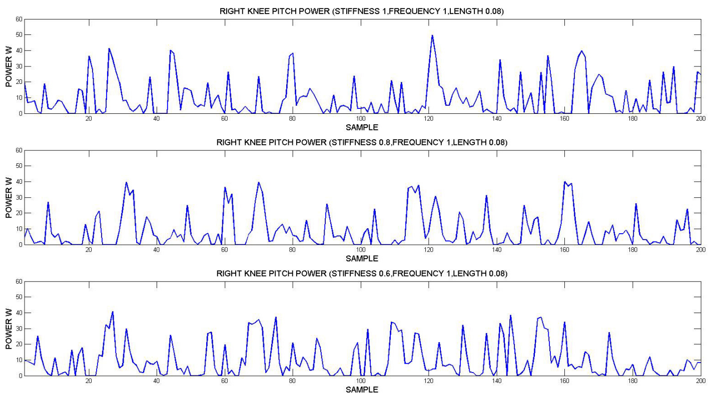


Fig. 8. Left Knee Pitch joint power usage at walking speed frequency 1 and step length 0.8 with the following stiffness (top) stiffness 1, (middle) stiffness 0.8, (bottom) stiffness 0.6

4.3 Ankle Pitch Joint

Figures 9, 10, and 11 show Ankle Pitch joint current, voltage and power for three stiffness values (1, 0.8 and 0.6) walking at maximum speed.

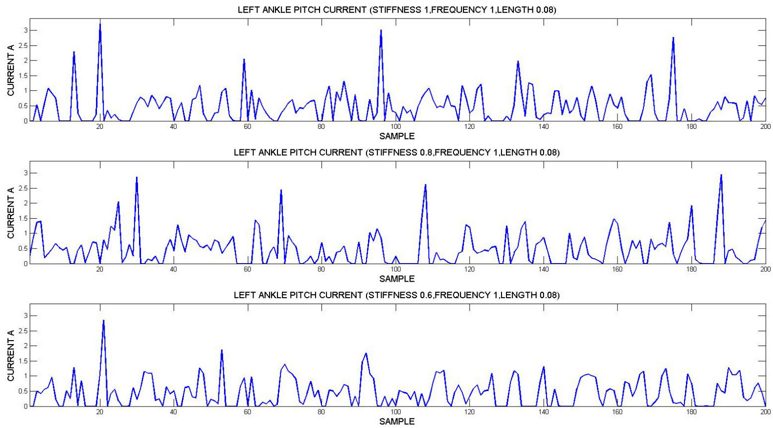


Fig. 9. Left Ankle Pitch joint current usage at walking speed frequency 1 and step length 0.8 with the following stiffness (top) stiffness 1, (middle) stiffness 0.8, (bottom) stiffness 0.6

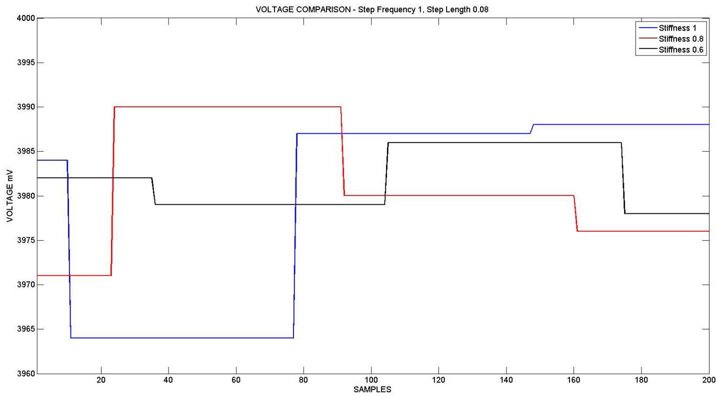


Fig. 10. Battery voltage usage for various Left Ankle Pitch joint stiffness at walking speed frequency 1 and step length 0.8: (black) stiffness 0.6, (red) stiffness 0.8, (blue) stiffness 1

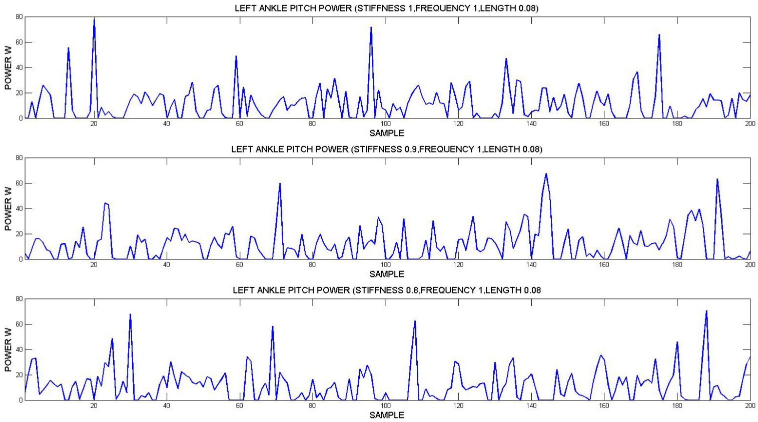


Fig. 11. Left Ankle Pitch joint power usage at walking speed frequency 1 and step length 0.8 with the following stiffness (top) stiffness 1, (middle) stiffness 0.8, (bottom) stiffness 0.6

4.4 Power and Energy Usage

Tables 2, 3, and 4 show max values of individual joint current and power for various stiffness values for Left Hip Pitch, Left Knee Pitch and Left Ankle Pitch. It is interesting to note that lowest current and power varies for various joints depending on stiffness. Note that when applying stiffness value under 0.6 walking becomes unstable with robot falling.

Table 2. Max current and power for Left Hip Pitch (Step Frequency 1, Step Length 0.08)

Stiffness	1	0.9	0.8	0.7	0.6
Current (A)	2.72	2.75	2.68	3.34	3.31
Power (W)	63.77	64.24	62.52	78.99	78.67

Table 3. Max current and power for Left Knee Pitch (Step Frequency 1, Step Length 0.08)

Stiffness	1	0.9	0.8	0.7	0.6
Current (A)	2.19	1.87	1.87	1.71	2.44
Power (W)	51.28	43.38	43.1	39.81	56.75

Table 4. Max current and power for Left Ankle Pitch (Step Frequency 1, Step Length 0.08)

Stiffness	1	0.9	0.8	0.7	0.6
Current (A)	3.31	3.77	3.00	2.78	2.84
Power (W)	78.71	88.51	70.47	65.44	67.94

Table 5 shows the accumulated power, i.e. total energy usage in Joules (J), for individual and total (grey) left and right joints according to the different stiffness values. Note the difference in energy usage for left and right side joints, whereas the Left and Right Hip Yaw Pitch have a unique motor controlling them both, hence their equal values.

Table 5. Total energy usage for individual joints and totals in Joules (J)

Stiffness	1	0.9	0.8	0.7	0.6
Left Hip Yaw Pitch (J)	5770	5668	5421	5540	5365
Left Hip Pitch (J)	15447	14751	14622	14188	14482
Left Hip Roll (J)	13358	13472	14197	14625	14486
Left Knee Pitch (J)	18236	18546	18675	18507	19105
Left Ankle Pitch (J)	22590	22017	21872	21166	21163
Left Ankle Roll (J)	4669	4906	4810	4956	5367
Total Left Joints (J)	80070	79360	79597	78982	79968
Right (Left) Hip Yaw Pitch (J)	5770	5668	5421	5540	5365
Right Hip Pitch (J)	12004	11380	11325	10956	11351
Right Hip Roll (J)	11557	11543	11306	11446	11394
Right Knee Pitch (J)	14954	14379	13315	12766	11619
Right Ankle Pitch (J)	14703	14964	14906	14882	15398
Right Ankle Roll (J)	5097	5043	5178	5112	4996
Total Right Joints (J)	64085	62977	61451	60702	60123
Total Joints (J)	144155	142337	141048	139684	140091

Tables 6 shows the resulting total energy usage per joint in Joules (J) when applying best stiffness values from Table 5 although keeping similar values for corresponding left and right joint. The total energy usage is reduced from 139684 Joules (Table 5 – Stiffness 0.7) to 138073 Joules (Table 6). This is a small 1% total energy usage reduction for a 1.5 min walk but exemplifies the use of variable stiffness control to reduce individual and total joint energy usage according to specific task.

Table 6. Total Energy Usage per Joint in Joules (Step Frequency 1, Step Length 0.08) for Left and Right Joints under variable stiffness values

Joint	Stiffness	Left Joints	Right Joints	Total Energy (J)
Left and Right Hip Yaw Pitch (J)	0.6	5448	5476	10924
Left and Right Hip Pitch (J)	0.7	14388	11487	25875
Left and Right Hip Roll (J)	0.7	13211	11501	24712
Left and Right Knee Pitch (J)	1	17460	14835	32295
Left and Right Ankle Pitch (J)	0.6	21261	14309	35570
Left and Right Ankle Roll (J)	1	4048	4677	8725
Total Joints (J)		75816	62285	138101

Table 7. Total Energy Usage per Joint in Joules (Step Frequency 1, Step Length 0.08) for Left and Right Joints for different stiffness values

Stiffness	1	0.9	0.8	0.7	0.6
Left Hip Yaw Pitch (J)	2893	8555	5925	3189	3300
Left Hip Roll (J)	21458	21464	21485	22571	20379
Left Hip Pitch (J)	10541	10345	9376	10065	12703
Left Knee Pitch (J)	22454	23508	18973	27085	29802
Left Ankle Pitch (J)	32743	21586	16827	13391	12877
Left Ankle Roll (J)	6961	4882	7560	5352	6131
Total Left Joints (J)	97050	90340	80146	81653	81925

Table 7 shows the total energy usage per joint in Joules (J) while the robot is standing for 1 minute. It is interesting to note that energy usage is relatively large when standing with stiffness values affecting the results.

Table 8 show the total energy usage per joint in Joules (J) for 1 minute walking at different step frequencies (0.1, 0.5 and 1) that proportionally control resulting walking speed. Stiffness is set to 1 for all experiments. Note that walking at 10% of max speed (0.1) results in about 80% of max speed energy usage.

Table 8. Total Energy Usage per Joint in Joules for various Walking Step Frequencies (0.1, 0.5, 1) while keeping Walking Step Length at 0.08 and Stiffness at 1

Step Frequency	0.1	0.5	1
Left Hip Yaw Pitch (J)	4186	4813	6812
Left Hip Pitch (J)	9613	10294	14365
Left Hip Roll (J)	14735	14462	14011
Left Knee Pitch (J)	12445	12643	15793
Left Ankle Pitch (J)	20004	21782	25147
Left Ankle Roll (J)	3012	2712	3936
Total Left Joints (J)	63995	66706	80065

5 Conclusions and Discussion

We have described in this paper results from our current research in analyzing during open-loop humanoid robot walking the effect of variations in motor stiffness over individual joints in terms of current, battery voltage, and power. During experiments we set the stiffness and walking parameters manually and performed readings on single joints to achieve the best possible sampling rate considering the logic restrictions when reading out data from the NAO. Data readings show relatively good correspondence to walking cycles. The results are very interesting in that power consumption and energy usage can be decreased by dynamically setting specific stiffness values at individual robot joints. The current analysis has been applied only to the NAO V4 robot while we are currently performing similar experiments to NAO V3 and looking to test on other humanoids and walking algorithms. In the current paper we have presented initial results of energy usage optimization. The long-term goal of our research is to better understand the relationship between stiffness control and energy usage depending on the particular humanoid configuration and task. In future work we will be extending the analysis to include other factors that affect energy usage such as battery drainage, joint load, friction and temperature.

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References

1. Mei, Y., Lu, Y.-H., Hu, Y.C., Lee, C.S.: A Case Study of Mobile Robot's Energy Consumption and Conservation Techniques. In: Proceedings of 12th International Conference on Advanced Robotics, ICAR 2005, Seattle, WA, July 18-20, pp. 492–497 (2005)
2. Zhang, W., Hu, J.: Low Power Management for Autonomous Mobile Robots Using Optimal Control. In: Proceedings of 46th IEEE Conference on Decision and Control, New Orleans, LA, December 12-14, pp. 5364–5369 (2007)
3. Ogawa, K., Kim, H., Mizukawa, M., Ando, Y.: Development of the Robot Power Management System Adapting to Tasks and Environments-The design guideline of the Power Control System Applied to the Distributed Control Robot. In: Proceedings of the SICE-ICASE International Joint Conference, Busan, Korea, October 18-21, pp. 2042–2042 (2006)
4. Yamasaki, F., Hosoda, K., Asada, M.: An Energy Consumption Based Control for Humanoid Walking. In: Proceedings of IEEE/RSJ International Conference Intelligent Robots and Systems, IROS 2002, Lausanne, Switzerland, September 30-October 4, vol. 3, pp. 2473–2477 (2002)
5. Kormushev, P., Ugurlu, B., Calinon, S., Tsagarakis, N.G., Caldwell, D.G.: Bipedal walking energy minimization by reinforcement learning with evolving policy parameterization. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2011, San Francisco, CA, September 25-30, pp. 318–324 (2011)
6. Kulk, J., Welsh, J.S.: A low power walk for the NAO robot. In: Proceedings of the Australian Conference on Robotics and Automation, Canberra, Australia, December 3-5 (2008)
7. Kulk, J., Welsh, J.S.: Autonomous optimisation of joint stiffnesses over the entire gait cycle for the NAO robot. In: Proceedings of the International Symposium on Robotics and Intelligent Sensors, IRIS 2010, Nagoya, Japan, March 6-11 (2010)
8. Kulk, J., Welsh, J.S.: Evaluation of walk optimisation techniques for the NAO robot. In: Proceedings of the 11th IEEE-RAS International Conference onHumanoid Robots, Bled, Slovenia, October 26-28, pp. 306–311 (2011)
9. Gouaillier, D., Hugel, V., Blazevic, P., Kilner, C., Monceaux, J., Lafourcade, P., Mariner, B., Serre, J., Maisonnier, B.: The NAO humanoid: A combination of performance and affordability. In: Proceedings of IEEE International Conference on Robotics and Automation, ICRA 2009, Kobe, Japan, May 12-17, pp. 769–774 (2009)
10. Vukobratovic, M., Borovac, B.: Zero-Moment Point- Thirty five years of its life. International Journal of Humanoid Robotics 1(1), 157–173 (2004)
11. Miura, H., Shimoyama, I.: Dynamic walk of a biped. The International Journal of Robotics Research 3(2), 60–74 (1984)
12. Kajita, S., Kanehiro, F., Kaneko, K., Yokoi, K., Hirukawa, H.: The 3D linear inverted pendulum mode: A simple modeling for a biped walking pattern generation. In: Proceedings of IEEE/RSJ Intelligent Robots and Systems, IROS 2001, Maui, Hawaii, USA, October 29-November 3, vol. 1(4), pp. 239–246 (2001)
13. Liu, X., Yang, R.: The simulated technology research of DC motor load. In: Proceedings of International Conference on Electronics and Optoelectronics, ICEOE 2011, vol. 3, July 29-31, pp. 375–377 (2011)
14. Aldebaran-Robotics, H25 Motor Documentation (2013), `http://www.aldebaran-robotics.com/documentation/family/nao_h25/motors_h25.html`
15. Movellan, J.: DC Motors (2010), `http://mplab.ucsd.edu/tutorials/DC.pdf`