2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Development of a Biped Locomotor with the Double Stage Linear Actuator

Yusuke Sugahara, *Advanced Research Institute for Science and Engineering, Waseda University*
Kenji Hashimoto, Nobutsuna Endo, Terumasa Sawato, Masamiki Kawase, Akihiro Ohta,
Chiaki Tanaka and Akihiro Hayashi, *Graduate School of Science and Engineering, Waseda University*
Hun-ok Lim, *Faculty of Engineering, Kanagawa University*
Atsuo Takanishi, *School of Science and Engineering, Waseda University*

***Abstract*- Previously, the realization of ascending and descending stairs and landing pattern modification control by WL-16RII were reported. However, it is difficult to use the landing pattern modification control when ascending stairs, because of the insufficient stroke of linear actuators. In this report, the design of a double stage linear actuator with a larger expansion and contraction ratio is described. The new linear actuators developed have been installed in WL-16RII, and several experiments were conducted. Through experiments involving walking with a wide step length and ascending a stair with landing pattern modification control, the effectiveness of the actuator developed is confirmed.**

I. Introduction

RECENTLY, to create a society where it is easy for elderly and disabled people to be self-reliant and participate, the "barrier-free" concept has been disseminated, and the scope of activity of elderly and disabled wheelchair users has expanded. However, under present circumstances, there remain many steps and considerable unevenness in the streets, for which they must always request others' help. To achieve a breakthrough towards the genuine realization of a barrier-free concept, the idea of "a locomotion robot as a form of barrier-free engineering methodology" is more effective than improving the infrastructure. This means by developing and providing a biped walking type wheelchair, with a locomotion mode equivalent to that of an able-bodied human and with equivalent mobility, the field of activity of wheelchair users can be dramatically enlarged.

The final target of our research involves developing a biped robot that is sufficient for practical use as a wheelchair for the elderly and disabled. We aim to provide a bipedal robot with only lower limbs and a waist capable of carrying a human. This biped walking vehicle would be applicable to the assistive technology field as a biped walking wheelchair; capable of ascending and descending stairs carrying a human.

Various research on walking robots for practical use was conducted by some researchers [1-6], and there has also been research into the biped walking type. Concerning a locomotion module capable of carrying a human, some research has also been conducted on the "Walking Chair" [5] or locomotion module called "My Agent" [6]. Moreover,

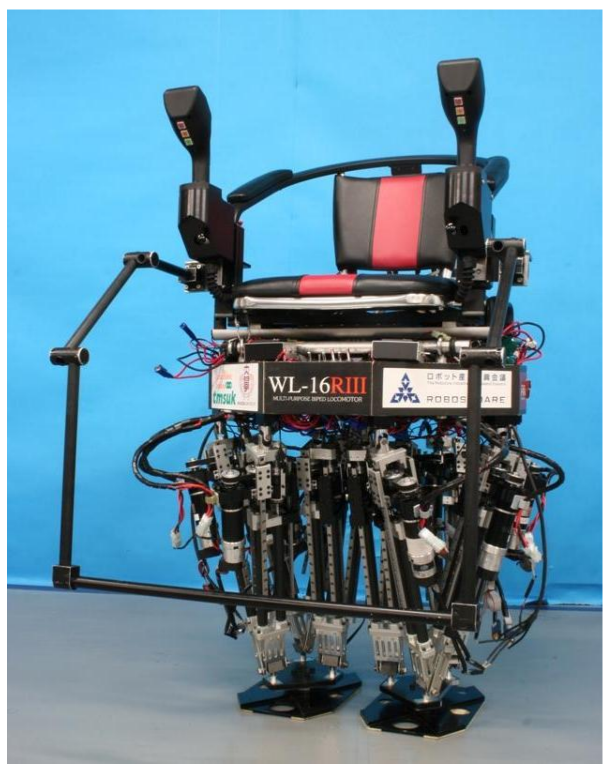

Figure 1. Waseda Leg – No. 16 Refined II with Double Stage Linear Actuators developed.

This research was performed in collaboration with TMSUK Co., Ltd. This research was supported by Fukuoka Prefecture, Fukuoka City and Solid Works Japan K.K. This study has been supported in part by the Ministry of Education, Science, Sports and Culture, via a Grant-in-Aid for Young Scientists (B), 16760208, 2004. Also, this study was supported in part by the Robotics Industry Development Council. This study was also supported in part by the "The innovative research on symbiosis technologies for human and robots in the elderly dominated society", 21st Century Center of Excellence Program, Japan Society for the Promotion of Science. The authors would like to thank them for their financial support.

in the welfare industry field, an electric wheelchair named "iBOT" [7], capable of ascending and descending stairs and slopes, was released by Independence Technology L.L.C., although it employed wheels for its locomotion mechanism. The Toyota Motor Corporation also announced the Toyota Personal Robot and "i-foot", which are biped human-carrying robots [8, 9].

Some of this research was conducted with the concept of reducing DOF [1, 2], while other projects focused only on ascending/descending stairs [3, 4] and some, moreover, did not focus on dynamic biped walking at all [5, 6]. Although these means are advantageous in terms of economy and ease, their goal is not versatility. Although "iBOT" is set for completion as one suitable style of locomotion system for riders, its objective does not include operation within a narrow environment, full of non-traversable items, such as a Japanese traditional house. Moreover, there are certain problems linked to its mechanism, such as the need for a rigid stair rail to ascend and descend stairs, and the inability to move sideways. Through limited information obtained on "i-foot", the unladen weight is revealed at 200 kg, although the payload is 60 kg, making it too heavy for a human-living environment.

Therefore, we developed some biped locomotors, WL-15 (Waseda Leg - No. 15), WL-16, WL-16R and WL-16RII, which have 6-DOF parallel mechanism legs [10-14]. This robot consists of two legs and a waist and is capable of walking independently, with an unladen weight of about 60 kg. Using this robot, we studied the way to apply the biped walking robot to a mobile base for a human locomotor. In November 2003, using WL-16, world firsts of a dynamic biped walking while carrying an adult woman and a dynamic biped walking while carrying a 60 kg adult man were realized [11, 12], preceding the release of Toyota Motor Corporation's Toyota Personal Robot.

For our final target, our biped locomotor must successfully ascend and descend stairs. In 2004, biped ascending and descending stairs carrying a human were realized using WL-16RII, refined hardware of WL-16 [13]. In a real environment, since no stairs can be said to have high dimensional accuracy, walking patterns are generated with each step rise precisely measured beforehand. It is important that a practical walking robot be able to detect and adapt to dimensional unevenness of the stairs automatically.

To solve this problem, landing pattern modification control using nonlinear compliance control was developed [14]. Although this control method was for walking on uneven terrain, it was also effective in ascending and descending stairs with an incline and subject to error, and by using this method, WL-16RII successfully ascended a stair with a rise of 150 mm, with an error of 20 mm.

Although this control method requires some margin of the movable range of the linear actuator, WL-16RII had no margin to ascend and descend 200 mm stairs. To use this control method in a more practical situation, a linear actuator with a larger stroke would be needed.

Another problem concerns minimum seat height. It is desirable to have a low minimum seat height and long strokes, because a high minimum seat height makes the robot difficult to ride. For this objective, a linear actuator with a small minimum length was needed.

This paper describes the development of a double stage linear actuator, with a high expansion and contraction ratio and that achieves a large stroke and small minimum length. This mechanism consists of two ball screws and gears that are driven by a single DC servo motor. The effectiveness of the developed mechanism is confirmed through experiments using revised linear actuators developed attached in WL-16RII.

II. Design Specifications

Figure 2 shows the link lengths to ascend a stair with a rise of 200 mm. Table 1 shows the minimum and maximum length and the stroke of the previous linear actuator, the required value to ascend a 200 mm stair and the design specifications of the double stage linear actuator.

As shown in Figure 2, there is no more than about a 10 mm margin for the upper and lower limit to ascend 200 mm stairs, and it is insufficient to use the landing pattern modification control.

To use the landing pattern modification control, 40 mm margin is needed for each limit. Therefore the required specification of the stroke has been set as 425 mm. On the

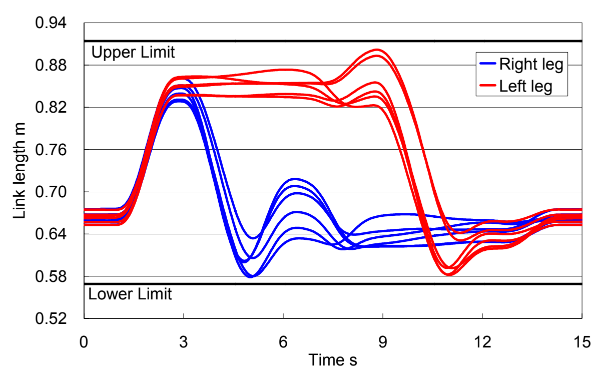

Figure 2. Link lengths to ascend a stair with a rise of 200 mm.

Table 1. Specifications of the linear actuator of WL-16RII and required specifications of the Double Stage Linear Actuator.

	Minimum length	Maximum	Stroke
Single linear actuator	569 mm	914 mm	345 mm
Requirement to ascend a stair with a rise of 200 mm	578 mm	902 mm	324 mm
Required specifications of the double stage linear actuator	489 mm	914 mm	425 mm

other hand, to reduce the minimum seat height, the minimum length of the linear actuator should be reduced, so the maximum length of the developed linear actuator was unchanged, and the minimum length was reduced.

III. Mechanical Design

Figure 3 shows the structure of the double stage linear actuator developed. This mechanism consists of two ball screws and gears that are driven by one DC servo motor. Two ball screws are located serially enabling a high expansion and contraction ratio to be obtained.

Screw nuts A and B are rotationally constrained. The motor rotation is then transferred to the ball screw A through pulleys and the timing belt, and the screw nut translates this rightward. This rotation is also transferred to the screw nut B through the gears A and B, and the ball screw B translates this leftward.

Figure 4 shows the photograph and Figure 5 shows the expanding motion of the double stage linear actuator developed. The exploded view is shown in Figure 6. The

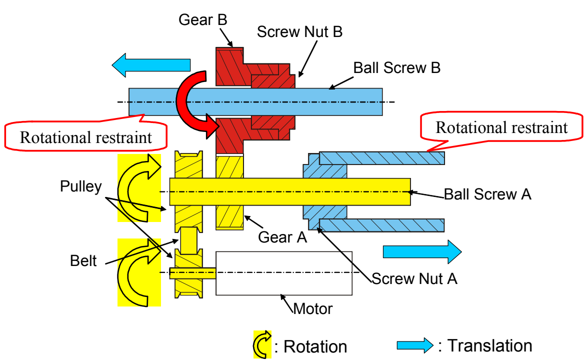

Figure 3. Structure of the double stage linear actuator.


Figure 4. The double stage linear actuator developed.

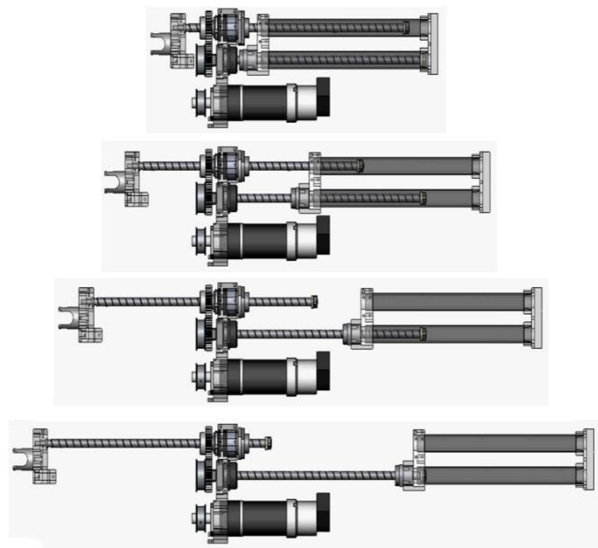
Figure 5. The expanding motion of the double stage linear actuator.

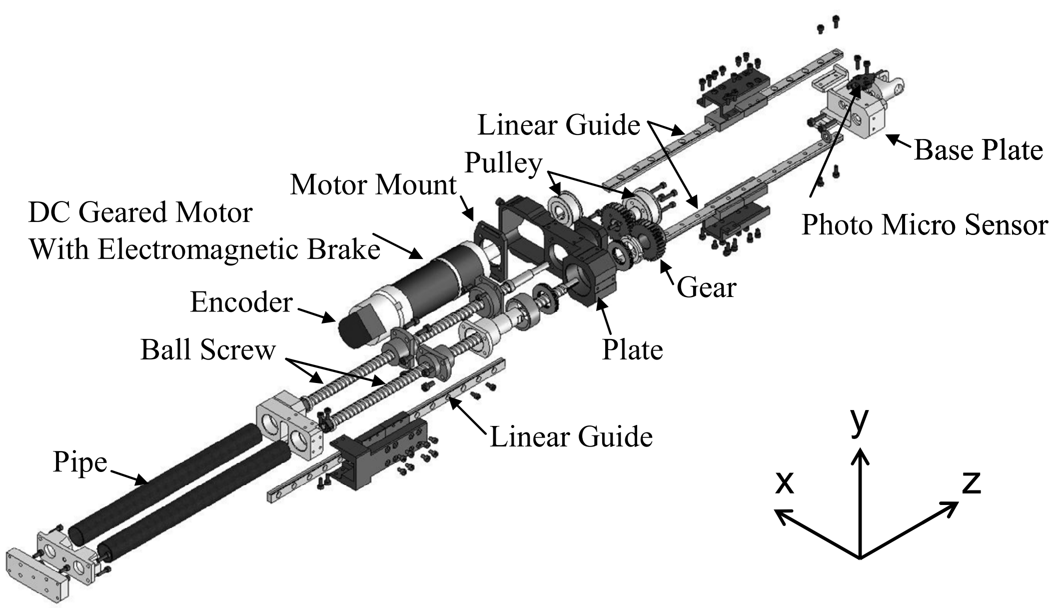

Figure 6. Exploded view of the double stage linear actuator developed.

Table 2. Specifications of the linear actuator for WL-16RII and the double stage linear actuator for WL-16RIII.

	Single stage linear actuator of WL-16RII	Double stage linear actuator of WL-16RIII
Minimum actuator length	468 mm	358 mm
Maximum actuator length	813 mm	814 mm
Stroke	345 mm	456 mm
Expansion and contraction ratio (actuator)	1.74	2.27
Reduction ratio (planetary gear)	3.5	3.5
Reduction ratio (pulley)	21 / 30	36 / 30
Screw lead	12 mm/rev	20 mm/rev (10 mm/rev x2)
Final reduction ratio	0.2041 rev/mm	0.2100 rev/mm
Weight	1900 g	2800 g

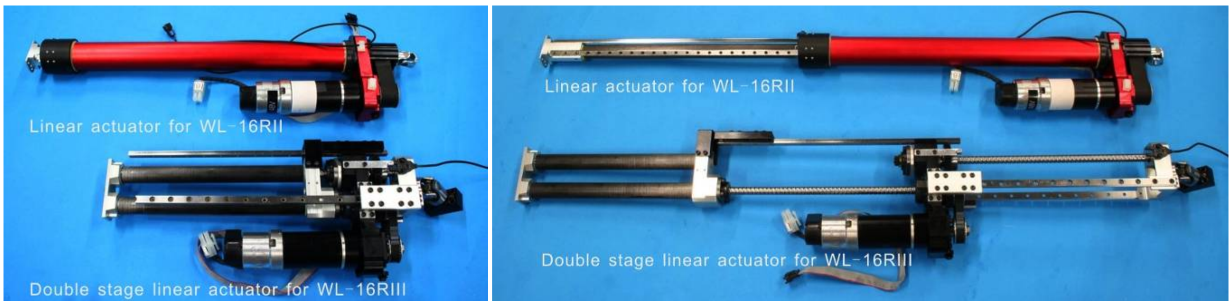

Figure 7. Comparison of the minimum and maximum length of the linear actuator.

specifications are described in Table 2.

Although the weight of the actuator has increased from 1900 g to 2800 g, the stroke increased by 110 mm and the expansion and contraction ratio of the actuator also increased from 1.74 to 2.27.

Figure 7 shows the comparison of the length of the WL-16RII's single stage actuator and WL-16RIII's double stage actuator. As shown in this figure, the minimum length has been reduced, although the maximum length remains unchanged.

IV. Experimental Tests

We conducted the following experiments using WL-16RIII with the double stage linear actuators developed to confirm the effectiveness of the developed hardware.

A. Comparison of the minimum seat height

Figure 8 shows the photographs of the robots at the condition of the minimum seat height. In the photographs, the two men are of almost equivalent body height. Comparing (a) and (b) shows that the minimum seat height has been reduced.

Figure 9 shows the value of the minimum seat height of WL-16RII and WL-16RIII.

B. Ascending a stair using the landing pattern modification control

An experiment ascending a stair using the landing pattern modification control was conducted.

The rise of the stair was 220 mm although the walking

(a) (b)

Figure 8. Photographs of the robot at the condition of the minimum seat height. (a): WL-16RII. (b): WL-16RIII with the double stage linear actuators developed.

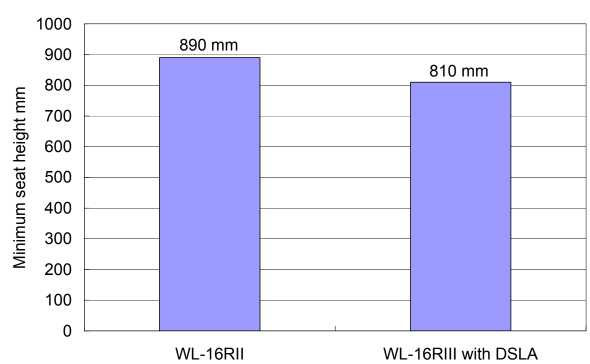

Figure 9. The minimum seat height.

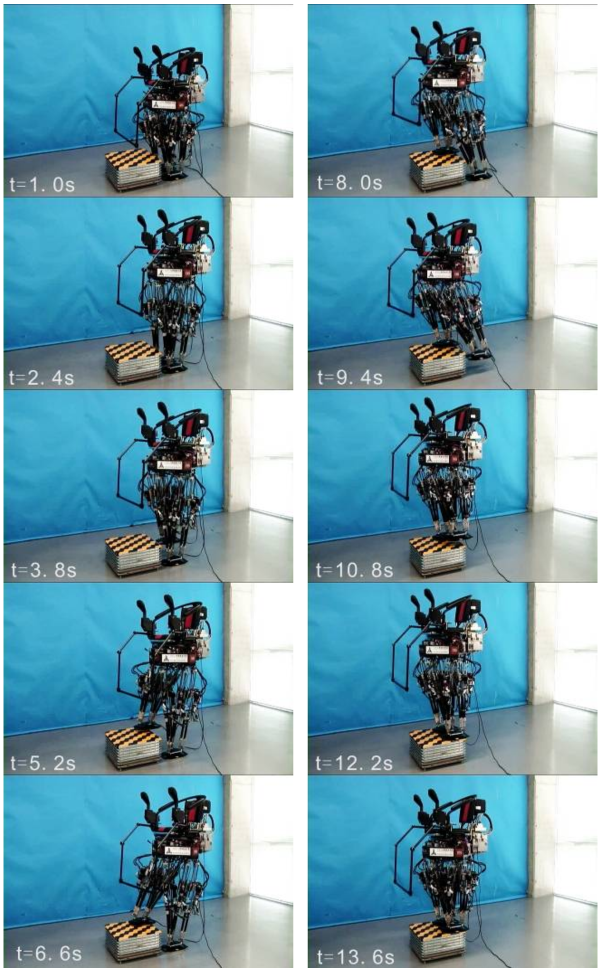

Figure 10. Views of the experiment ascending a stair with a rise of 220 mm using landing pattern modification control.

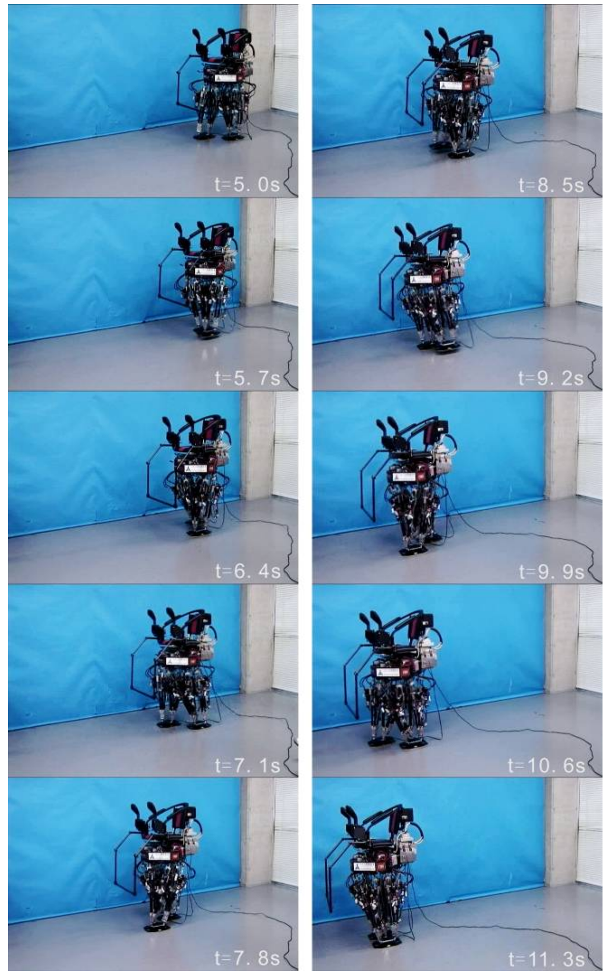

Figure 12. Views of the walking experiment with a step length of 300 mm and walking cycle of 0.96 s/step.

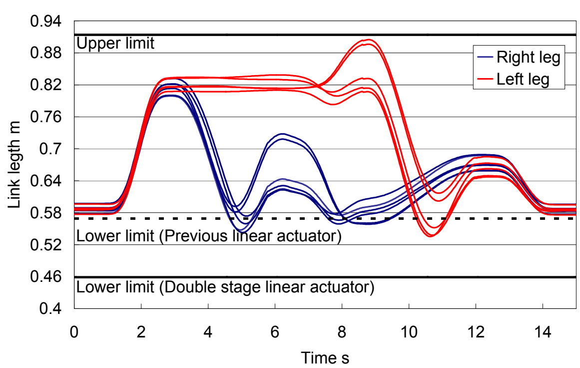

Figure 11. The link length trajectories of the experiment ascending a stair.

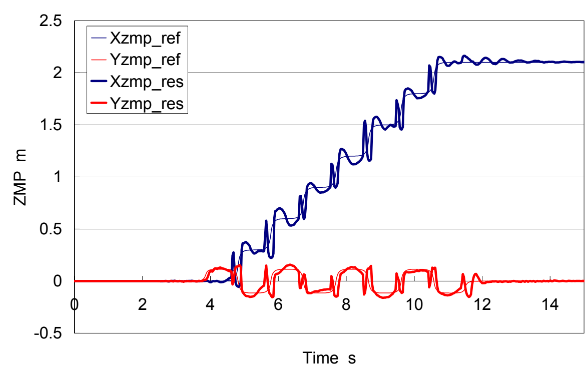

Figure 13. ZMP trajectories of the walking experiment.

pattern generated beforehand was for a 200 mm stair. WL-16RIII, with the double stage linear actuators developed, succeeded in stably ascending the stair.

Figure 10 shows the views of the experiment, and Figure 11 shows the link length trajectories of the experiment.

As has been mentioned, the landing pattern modification control needs some margin of the movable range of the linear actuator. As shown in Figure 11, this control method could not be used with previous linear actuators, but was usable with the double stage linear actuators, developed because of their large stroke. The effectiveness of this mechanism has thus been confirmed.

C. Walking experiment with a step length of 300 mm and walking cycle of 0.96 s/step

WL-16RII could not walk with a step length of 300 mm and walking cycle of 0.96 s/step because of the critical speed of its linear actuator. The double stage linear actuator developed consists of two ball screws, and the revolution of one ball screw, required to expand the same displacement, is half that of the previous linear actuator. Therefore, the limit on the maximum expansion and contraction speed, imposed by the critical speed of the ball screw, has been eased.

To confirm this advantage, a walking experiment with a step length of 300 mm and walking cycle of 0.96 s/step was conducted.

Figure 12 shows the views of the experiment, and Figure 13 shows its ZMP trajectories.

s shown in these figure, WL-16RIII succeeded in walking stably with the double stage linear actuator developed, and its effectiveness was confirmed.

V. Conclusions and Future Work

To increase the stroke and reduce the minimum seat height, a double stage linear actuator was developed. This mechanism consists of two ball screws and gears, and is driven by one DC servo motor. Two ball screws are located serially, enabling a high expansion and contraction ratio to be attained. Stroke was increased, the height of the seat was decreased and the critical speed was increased.

By using the double stage linear actuator developed, ascending a stair with a height of 220 mm using landing pattern modification control was realized. Stable dynamic walking with a walking cycle of 0.96s and step length of 300 mm was also achieved.

Through the experiments, the effectiveness of the double stage linear actuator developed was confirmed.

Our next goal involves evaluating the loading capacity, reducing the backlash and developing a more reliable linear actuator.

Moreover, to achieve a biped wheelchair sufficient for practical use, we will also continue to study various mechanisms and control methods effective in terms of stability, safety and cost reduction.

Acknowledgment

This study has been conducted as part of the humanoid project at the Humanoid Robotics Institute, Advanced Research Institute for Science and Engineering, Waseda University.

References

[1] K. Takita, et al., "Fundamental mechanism of dinosaur-like robot TITRUS-II utilizing coupled drive," Proc. of the IEEE/RSJ IROS 2000, pp. 1670-1675, Takamatsu, Japan, October, 2000.

[2] Y. Ota, T. Tamaki, K. Yoneda and S. Hirose, "Development of walking manipulator with versatile locomotion," Proc. of the IEEE ICRA 2003, pp. 477-483.

[3] Y. Konuma and S. Hirose, "Development of the stair-climbing biped robot "Zero Walker-1"," Proc. of the 19th Annual Conf. of the RSJ, pp. 851-852, 2001 (in Japanese).

[4] Y. Konuma and S. Hirose, "Development of 2 types of leg-wheel vehicle with the function of stable stair-climbing," Proc. of the 8th RSJ/JSME/SICE Robotics Symposia, pp. 160-167, Shizuoka, Japan, March, 2003 (in Japanese).

[5] Y. Takeda, M. Higuchi and H. Funabashi, "Development of a walking chair (Fundamental investigations for realizing a practical walking chair)," Proc. of the CLAWAR2001, pp. 1037-1044, Karlsruhe, Germany, September, 2001.

[6] T. Kamada, "My Agent: A Practical Personal Assistant," Proc. of the JSME ROBOMEC '94, pp. 1107-1112, Kobe, Japan, 1994 (in Japanese).

[7] http://www.independencenow.com/ibot/index.html.

[8] http://www.toyota.co.jp/en/special/robot/index.html, March 11th, 2004.

[9] http://www.toyota.co.jp/en/news/04/1203_1d.html, December 3rd, 2004.

[10] Y. Sugahara, et al., "Design of a Battery-powered Multi-purpose Bipedal Locomotor with Parallel Mechanism," Proc. of the IEEE/RSJ IROS 2002, pp. 2658-2663, Lausanne, Switzerland, October, 2002.

[11] Y. Sugahara, et al., "Realization of Dynamic Walking by a Biped Locomotor Carrying a Human," Proc. of the 9th RSJ/JSME/SICE Robotics Symposia, pp. 96-101, Okinawa, Japan, March 8th-9th, 2004 (in Japanese).

[12] Y. Sugahara, et al., "Realization of Dynamic Human-Carrying Walking by a Biped Locomotor," Proc. of the IEEE ICRA 2004, pp. 3055-3060, New Orleans, USA, April, 2004.

[13] Y. Sugahara, et al., "Walking Up and Down Stairs Carrying a Human by a Biped Locomotor with Parallel Mechanism," Proc. of the IEEE/RSJ IROS 2005, pp. 3425-3430, Edmonton, Canada, August, 2005.

[14] K. Hashimoto, et al., "Biped Landing Pattern Modification Method with Nonlinear Compliance Control," Proc. of the IEEE ICRA 2006, pp.1213-1218, Orlando, USA, May, 2006.