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RESEARCH ARTICLE

Limb Stiffness Improvement of the Robot WAREC-1R for a Faster and Stable New Ladder Climbing Gait

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Abstract
Ladder climbing is a relatively new but practical locomotion style for robots. Unfortunately, due to their size and weight, ladder climbing by human-sized robots developed so far is struggling with the speedup of ladder climbing motion itself. Therefore, in this paper, a new ladder climbing gait for the robot WAREC-1R is proposed by the authors, which is both faster than the former ones and stable. However, to realize such a gait, a point that has to be taken into consideration is the deformation caused by the self-weight of the robot. To deal with this issue, extra hardware (sensor) and software (position and force control) systems and extra time for sensing and calculation were required. For a complete solution without any complicated systems and time only for deformation compensation, limb stiffness improvement plan by the minimal design change of mechanical parts of the robot is also proposed by the authors, with a thorough study about deformation distribution in the robot. With redesigned parts, ladder climbing experiments by WAREC-1R proved that both the new ladder climbing gait and the limb stiffness improvement are successful, and the reduced deformation is very close to the estimated value as well.

Keywords Ladder climbing · Legged robot · Bionic robot · Gait · Stiffness improvement · Finite element analysis

1 Introduction

Ladder climbing performed by robots has emerged into researchers' sight in recent decades as a relatively new solution to locomotion tasks in vertical direction. Beginning from LCR-1 [1] developed in 1989, a robot with 4 grippers for grasping rungs in ladder climbing, bio-inspired robots in various forms and scales have been developed for ladder climbing tasks. They include Gorilla-III [2–5] that mimics the shape and size of a gorilla, hexapod robot ASTERISK [6] that mimics insects, Felidae-like robot [7], snake robot [8, 9] and a main branch of robot ladder climber: human-sized robots with 4 limbs, which is also the main concern of this paper. Robots belonging to this category are DRC-Hubo [10], Atlas [11] (these two robots climbed inclined ladders instead of vertical ones), HRP-2 [12, 13], E2-DR [14, 15] and robots [16–24] developed by the authors. Generally speaking, human-sized robots with 4 limbs have the advantage of versatility in locomotion styles (legged walking, crawling and others) besides ladder climbing and the capability of manipulation with high power [17] in comparison with other types of bio-inspired robot ladder climbers. Therefore, there are high expectations for the application of these robots in disaster response, infrastructure maintenance, space exploration, teleoperation and other fields.

However, a potential drawback to be improved for the ladder climbing of human-sized robots is the climbing speed. Unlike other locomotion tasks, once falling from a ladder, it is almost impossible for a human-sized robot climber to survive due to the huge damage caused by falling. Consequently, in ladder climbing of a human-sized robot stability has the highest priority, and in the former studies [10–15], this conservative strategy usually leads to the compromise of ladder climbing speed. A representative example is the gait of ladder climbing, which can be defined as the order and number of limbs to move in the climbing motion. Specifically, ladder climbing gaits can be divided into two main types: (1) 3-point contact gaits, which are very easy to maintain stability but slower and (2) 2-point contact gaits, which are much faster but there is risk of losing stability if the posture of robot and force/torque around the contact points

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are not appropriate. For human-sized ladder climbing robots known, 2-point contact gait is rarely used until the robots developed by the authors [19, 21]. Unfortunately, although the authors succeeded in guaranteeing stable ladder climbing in 2-point contact gait that is faster than 3-point contact gaits, both the hardware and software system become more convoluted than before. Therefore, in this paper a new ladder climbing gait is proposed, discussed in detail and demonstrated, which aims at stable ladder climbing that is faster than the achieved 2-point contact ones with no need of additional hardware and software systems.

Through verification experiments of the new gait, it is confirmed that the improvement of limb stiffness to decrease the deformation is necessary for such a new, stable, efficient and simple ladder climbing gait. According to this fact, thorough study and discussions are made to determine the solution plan: minimal design change of structural parts to reinforce the "weak points" that deform most in the limbs of robot. Distribution of deformation is identified quantitatively by utilizing motion capture and Finite Element Analysis (FEA). Subsequently, based on all the requirements given, redesigned parts are manufactured and replace the corresponding old parts. The results of the ladder climbing experiments in the new gait prove that both the proposed ladder climbing gait and the limb stiffness improvement are effective and the estimated deformation decrease is very close to the real value.

This paper is organized as follows: Section 2 briefly describes the feature of WAREC-1R and its end-effector as the knowledge that should be known in advance. Section 3 introduces the ladder climbing of WAREC-1R and discusses different gaits of ladder climbing with their characteristics to propose a new ladder climbing gait with its detailed whole-body motion planning algorithms. Section 4 determines the solution to deformation as well as detailed requirements for the solution to realize the proposed new ladder climbing gait and shows the results of deformation distribution analysis. Based on all the requirements and analysis results, new designs of structural parts are shown. Section 5 presents the experiments for verification of the proposed new ladder climbing gait and the evaluation of limb stiffness improvement. Finally, Sect. 6 summarizes the entire paper and future works.

2 Introduction of WAREC-1R

WAREC-1R (WAseda REsCuer-No.1 Refined) is the human-sized four-limbed robot developed by Takanishi Laboratory, Waseda University, Japan as the refined robot of its previous version, WAREC-1 [17]. Its specification, design concepts and locomotion performance are introduced in the previous paper of the authors [21]. With the

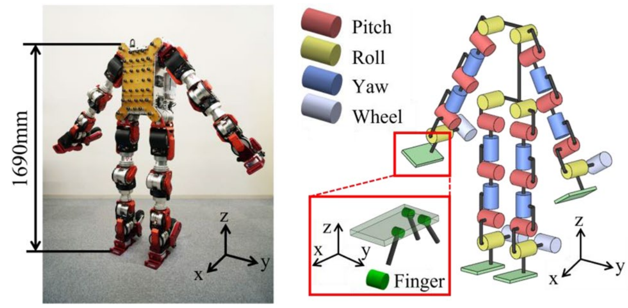


Fig. 1 Overview and DoF configuration of WAREC-1R

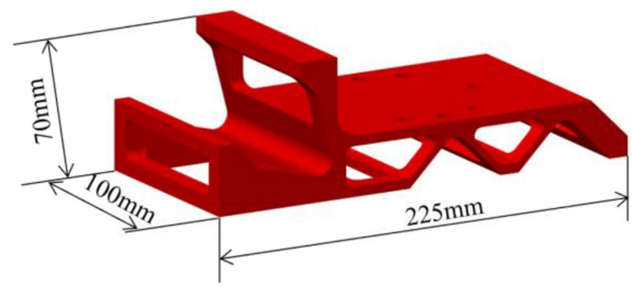


Fig. 2 End-effector of WAREC-1R in CAD model with scales

height of 1.69 m and weight of 179 kg, WAREC-1R's Degree of Freedom (DoF) configuration is depicted in Fig. 1. More details can be seen in Ref [25].

Basic sensors in WAREC-1R are one force/torque sensor at each end-effector (4 in total) and one Inertial Measurement Unit (IMU) inside its body. Its optional sensors include depth cameras, Laser Range Finders, proximity sensors and others that can be equipped on its back.

Aiming at a robotic solution to disasters, inspection, remote maintenance of infrastructures/plants and other tasks that are hazardous or even impossible for human to perform, WAREC-1R has achieved tasks including vertical ladder climbing [18–21], biped/quadruped walking, stair climbing, wheel driving, crawling [23, 24] and remote manipulation. All 4 limbs of WAREC-1R share completely the same design for the symmetry in both up-down and left–right direction. This characteristic is significant for the compatibility of all limbs and robustness when one of 4 limbs is malfunctioning or out of control. Meanwhile, end effectors [26] of WAREC-1R shown in Fig. 2 also have the identical design that can be used for either hand or foot in ladder climbing and enable surface contact for legged stance. The main material of the robot is 7075 Aluminum Alloy (AA7075).

Figure 3 shows locomotion and manipulation tasks that WAREC-1R is capable of and ladder climbing is the main concern in this paper. Among all these tasks, ladder climbing is also the one with the highest requirement of position

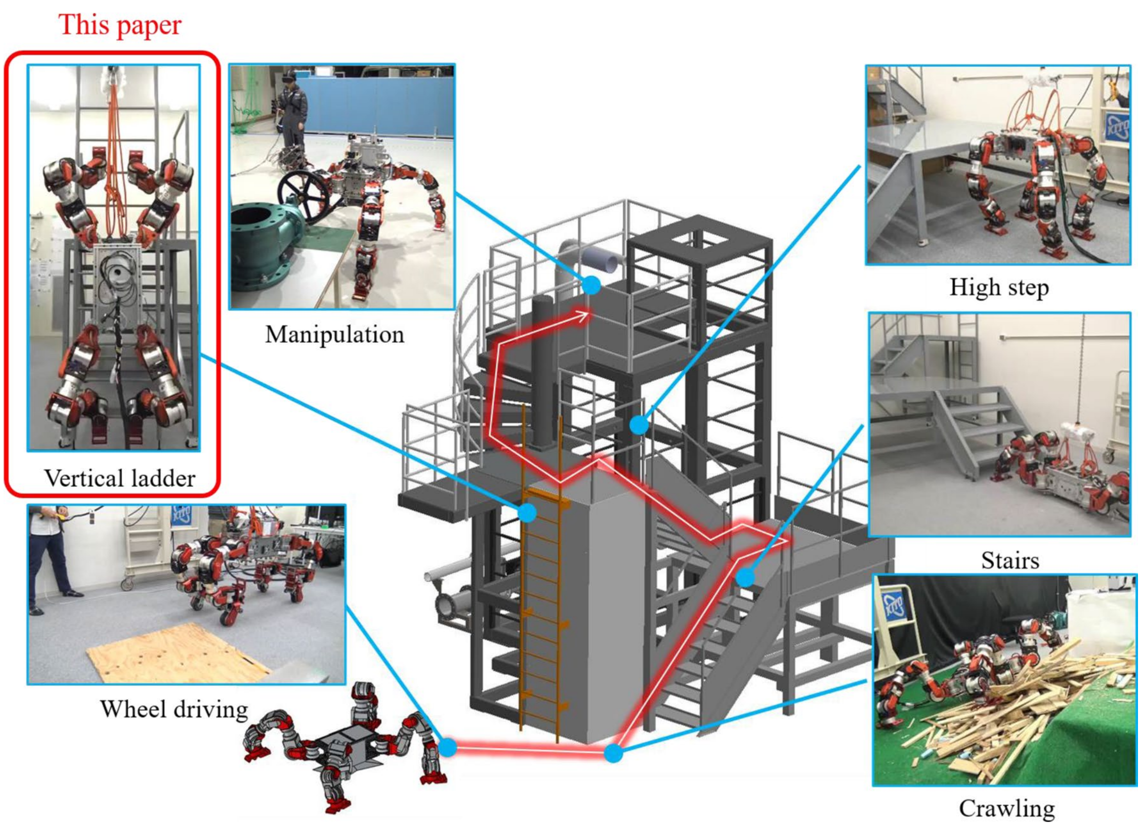


Fig. 3 Tasks that WAREC-1R is capable of

accuracy for end-effector, thus is the most sensitive one to the deformation as well.

3 Ladder Climbing of WAREC-1R: Discussion and Proposition of Gaits

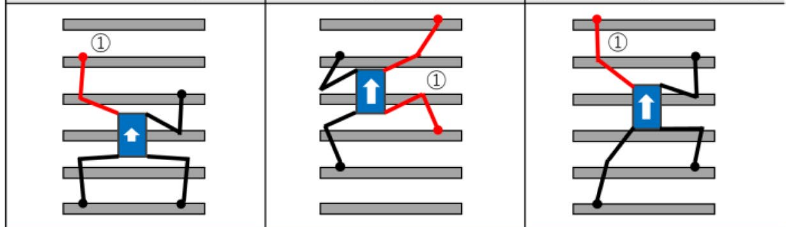
Ladder climbing by human-sized robots has been studies by authors for years, including researches about trajectory planning [18], motion planning for stability [19] and high speed climbing in 2-point contact gait with the capability of rung recognition [20, 21]. In the following contents of this paper, gait will be mainly discussed for faster and stable ladder climbing.

3.1 Discussion of Ladder Climbing Gaits

For 3-point contact gaits, the robot moves its limbs one by another so that there are always at least 3 contact points between the robot and ladder. Similarly, for 2-point contact gaits, the robot moves its 2 limbs simultaneously ("pace" for 2 limbs on the same side and "trot" for 2 limbs on different sides) so that there are always at least 2 contact points between the robot and ladder. As is listed and compared in Fig. 4, they have completely different features. Generally speaking, 2-point contact gaits are faster than 3-point contact gaits because it takes fewer steps to climb up or down a rung than 3-point contact gaits. However, as the expense ladder climbing in 2-point contact gaits has much higher risk of losing stability because during the 2-point contact period the robot might start rotating around the axis connecting 2 contact points (Axis of Yawing) [3, 4], which causes the failure of ladder climbing, yet it is almost impossible to occur in 3-point contact gaits. This is also the reason that motion and force control is required to guarantee stability in 2-point contact gaits.

In our previous studies, stable 2-point contact ladder climbing has been a major target. To realize such a goal, systems of (1) posture control (2) reaction force control and (3) proximity sensor system for rung recognition are proposed and constructed [21]. Comparing to the conventional 3-point contact ladder climbing gait of transverse, which is the gait that has been applied for most of the former studies, 2-point contact ladder climbing implemented by the authors is faster (approximately 89% faster than transverse), capable of recognizing ladder rungs and stable as well. Unfortunately, it is not perfect. Its overall system is complicated in both hardware and software level and some of them (posture control and rung recognition) spend extra time, and the ladder climbing could have been faster without them.

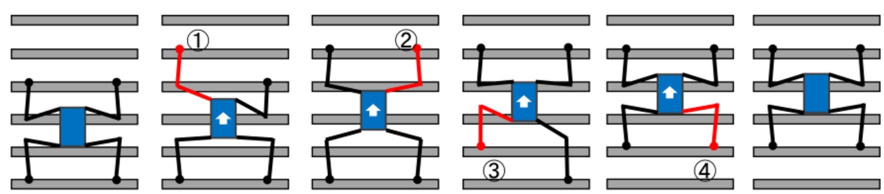
Fig. 4 Comparison of different gaits

	3-point contact (transverse)	2-point contact (pace)	This paper 3-point contact (one rung skipping)
Ladder climbing gaits			
Climbing stability	Easy to maintain	Posture and force control required	Easy to maintain
Climbing speed m/h	28	53	> 53
System	Simple	Complicated	Simple

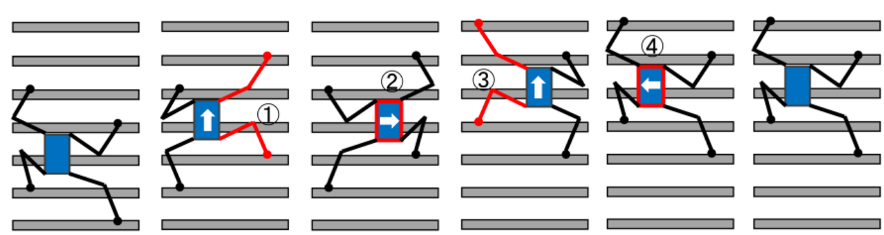
3.2 Proposition of the New Ladder Climbing Gait

To realize faster and stable ladder climbing without complicated posture, force control and proximity sensor system, a new 3-point contact ladder climbing gait called one rung skipping 3-point contact gait is proposed and mainly discussed in this paper. As is illustrated in Fig. 5(c), it fully takes advantage of the end-effector workspace, vertical body movement and the order of limbs to move, so that WAREC-1R becomes capable of climbing up/down two rungs instead of one rung for the conventional transverse gait shown in Fig. 5(a), in the same 4 steps. Apparently, the proposed new gait is faster (theoretically it would be twice of traditional transverse in speed if it takes the same time for each step),

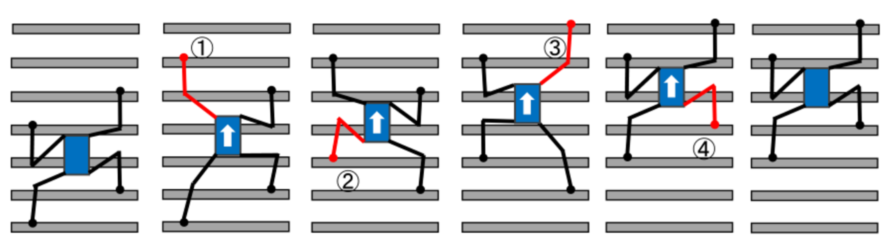
Fig. 5 Breakdown of three ladder climbing gaits in steps



(a) Flow of the conventional 3-point contact ladder climbing gait (transverse): 1 rung in 4 steps.



(b) Flow of a 2-point contact ladder climbing gait (pace): 2 rungs in 4 steps.
② and ④ are posture control for maintaining stability.



(c) Flow of one rung skipping 3-point contact ladder climbing gait: 2 rungs in 4 steps.

and since it is a 3-point contact ladder climbing gait, there is no need of posture control or reaction force control to maintain stability, which are indispensable in 2-point contact ladder climbing. In another word, this new climbing gait provides another option that guarantee stability and faster climbing speed when necessary besides the traditional 3-point contact climbing gait.

3.3 Whole-body Motion Planning of the New Ladder Climbing Gait

With the new ladder climbing gait introduced above, its specific algorithms about whole-body motion planning are briefly presented here.

In our case, the trajectory of robot body and end effectors are planned separately. To begin with, set $\boldsymbol{\gamma}_{\mathrm{B}}$, $\boldsymbol{\gamma}_{\mathrm{BE}i}$ and $\boldsymbol{\gamma}_{\mathrm{E}i}$ as the trajectory of the body (at its center point), the trajectory of end effector in the i_{th} limb with respect to the body and the trajectory of end-effector in the i_{th} limb in world coordinate system, respectively. The origin is defined as the middle point of the lowest ladder rung and the coordinate system is defined in Fig. 1. Then we have

$$\boldsymbol{\gamma}_{\mathrm{B}}(t) = (x_{\mathrm{B}}(t), y_{\mathrm{B}}(t), z_{\mathrm{B}}(t))^T, \tag{1}$$

$$\boldsymbol{\gamma}_{\mathrm{BE}_i}(t) = (x_{\mathrm{BE}_i}(t), y_{\mathrm{BE}_i}(t), z_{\mathrm{BE}_i}(t))^T, \tag{2}$$

$$\boldsymbol{\gamma}_{\mathrm{E}_i}(t) = (x_{\mathrm{E}_i}(t), y_{\mathrm{E}_i}(t), z_{\mathrm{E}_i}(t))^T, \tag{3}$$

$$\boldsymbol{\gamma}_{\mathrm{E}_i} = \boldsymbol{\gamma}_{\mathrm{B}} + \boldsymbol{\gamma}_{\mathrm{BE}_i}, \tag{4}$$

where $t \in [t_0, t_{\mathrm{f}}]$ is the time, t_0 is the initial time of ladder climbing, t_{f} is the terminal time of ladder climbing and $i = 1$, 2, 3, 4 is defined as the number of limb, with the right upper limb as 1, left upper limb as 2, right lower limb as 3 and left lower limb as 4.

As for the detailed trajectory of each end effector, cubic spline interpolation combined with path-time independent trajectory planning [18] previously proposed by the authors are implemented. The path planning is given by cubic spline curves based on 3 predetermined mid-points and time profile of the trajectory set as an S-shaped curve to realize smooth trapezoidal drive. And $\boldsymbol{\gamma}_{\mathrm{BE}i}$ can be given as

$$x_{\mathrm{BE}_i}(t) = a_{xi} + b_{xi}(t - t_0) + c_{xi}(t - t_0)^2 + d_{xi}(t - t_0)^3, \tag{5}$$

$$y_{\mathrm{BE}_i}(t) = a_{yi} + b_{yi}(t - t_0) + c_{yi}(t - t_0)^2 + d_{yi}(t - t_0)^3, \tag{6}$$

$$z_{\mathrm{BE}_i}(t) = a_{zi} + b_{zi}(t - t_0) + c_{zi}(t - t_0)^2 + d_{zi}(t - t_0)^3. \tag{7}$$

More details can be found in Ref. [18] and are omitted here.

Meanwhile, in a complete motion cycle, the following constraints should be satisfied to make sure that it is repeatable:

$$z_{\mathrm{E}_i}(t_{\mathrm{f}}) - z_{\mathrm{E}_i}(t_0) = 2d_{\mathrm{rung}}, \tag{8}$$

$$z_{\mathrm{B}}(t_{\mathrm{f}}) - z_{\mathrm{B}}(t_0) = 2d_{\mathrm{rung}}, \tag{9}$$

where d_{rung} is the ladder rung interval.

Specifically, for the smoothness of ladder climbing, the trajectory of body in a complete ladder climbing cycle is set as uniform linear motion expressed as

$$\boldsymbol{\gamma}_{\mathrm{B}}(t) = (x_{\mathrm{B}_0}, y_{\mathrm{B}_0}, 2d_{\mathrm{rung}} \cdot \left(\frac{t - t_0}{t_{\mathrm{f}} - t_0}\right) + z_{\mathrm{B}_0})^T, \tag{10}$$

which satisfies the constraint of Eq. (9) and $\boldsymbol{\gamma}_{\mathrm{B0}} = (x_{\mathrm{B0}}, y_{\mathrm{B0}}, z_{\mathrm{B0}})^{\mathrm{T}}$ is the initial position of the body. Thus we also have the constraint below about the relative trajectory of an arbitrary end effector in the motion of an arbitrary limb (1/4 cycle) among one complete climbing cycle

$$z_{\mathrm{BE}_i}(\frac{t_{\mathrm{f}} - t_0}{4} \cdot l + t_0) - z_{\mathrm{BE}_i}(\frac{t_{\mathrm{f}} - t_0}{4} \cdot (l - 1) + t_0) = \frac{3}{2} d_{\mathrm{rung}} \tag{11}$$

according to Eq. (4), Eq. (9) and the fact that the body goes up for $(1/2)d_{\mathrm{rung}}$ for each 1/4 cycle, where $l = 1, 2, 3, 4$ is the order of the i_{th} limb to move.

3.4 Initial Posture and the Order of Limbs to Move in the New Gait

As is illustrated in Fig. 5 and explained in Sect. 3.2, in the new ladder climbing gait, much longer distances will be traveled by both end effectors and the body of robot in comparison with the traditional transverse gait, which means that longer reachable distance is required for each end-effector as well. Table 1 shows the relative distance that each end

Table 1 Analysis of the distance to move for each limb in each phase

Limb order	Change of $z_{\mathrm{BE}i}$ in each phase			
	Phase			
1st	$+(3/2)\ d_{\mathrm{rung}}$ Swing	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$-(1/2)\ d_{\mathrm{rung}}$ Stance
2nd	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$+(3/2)\ d_{\mathrm{rung}}$ Swing	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$-(1/2)\ d_{\mathrm{rung}}$ Stance
3rd	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$+(3/2)\ d_{\mathrm{rung}}$ Swing	$-(1/2)\ d_{\mathrm{rung}}$ Stance
4th	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$-(1/2)\ d_{\mathrm{rung}}$ Stance	$+(3/2)\ d_{\mathrm{rung}}$ Swing

effector travels long Z-axis in a complete cycle of ladder climbing with the new gait. Apparently, the whole cycle can be divided in 4 parts with each limb moves up. Using the terms in biped walking, the state of each end-effector can also be divided into two types: (1) swing phase with end-effector in the air and (2) stance phase with end-effector in contact with ladder rungs. Then it is clear that among 4 parts in the cycle there must be one for swing phase and the remaining 3 for stance phase, but their order would be different with the order of limbs to move.

Based on the analysis above, crucial points for the new gait are: (1) guaranteeing sufficient reachable distance in Z-axis for each end-effector; (2) rational order of limbs to move and arrangement of reachable distance for each end-effector to fit the difference shown in Table 1.

Reachable distance of each end-effector can be obtained by kinematics of the robot described in Ref. [19] and $\boldsymbol{\gamma}_{\mathrm{BE}i}$. Set $d_{iz\mathrm{lim}-}$ and $d_{iz\mathrm{lim}+}$ as the maximal reachable distance of end-effector in the i_{th} limb in + Z-axis and in –Z-axis, respectively, then the initial posture of robot ($\boldsymbol{\gamma}_{\mathrm{BE}i}$) is determined such that

$$\max\{d_{iz\lim+}\} > \frac{3}{2}d_{\mathrm{rung}}, \tag{12}$$

$$\max\{d_{iz\lim-}\} > \frac{3}{2}d_{\mathrm{rung}}, \tag{13}$$

$$\left|z_{\mathrm{E}j} - z_{\mathrm{E}k}\right| = \mathrm{n}d_{\mathrm{rung}}, \tag{14}$$

where j, k = 1,2,3,4 and are different from each other, and n is a non-negative integer.

With initial posture fixed, the number of limb to move next at an arbitrary moment in the new ladder climbing gait can be determined by:

$$i^* = \arg\max_i\{d_{iz\lim+}\}. \tag{15}$$

In another word, the end effector with the largest $d_{iz\mathrm{lim}+}$ would always be moving up next.

3.5 Issues Occurred in the New Gait

The idea of the new 3-point contact ladder climbing as well as its motion planning described in Sect. 3.3 and 3.4 has been verified to be feasible in Gazebo simulator with the middleware of ROS and Ubuntu OS, which is depicted in Fig. 6. However, it is not the case for the real robot due to the deformation of the robot limbs presented in Fig. 7, which brings out another topic of this paper: the solution to deformation difference at joints for faster and stable ladder climbing. Note that in this paper, other factors that may also cause the position error in Fig. 7, such as rigid body size, ladder rung length, vibration under operation, elastic deformation and so on, are not within the scope of this paper.

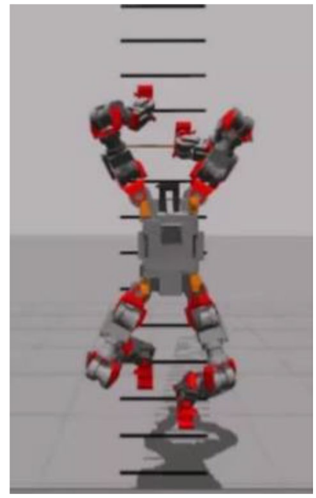


Fig. 6 Verification of the new proposed ladder climbing gait in simulation

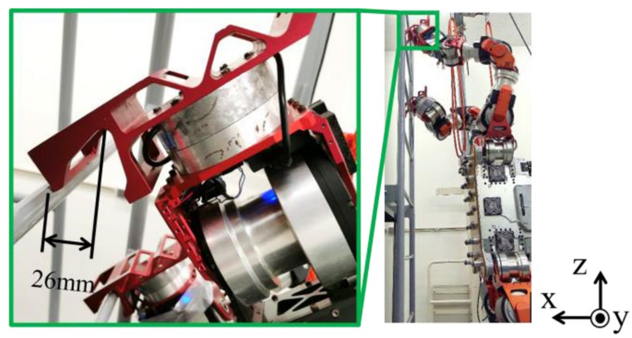


Fig. 7 The position error in X-axis due to the deformation in the new ladder climbing gait

4 Limb Stiffness Improvement

As a matter of fact, deformation of the robot has always been a threat to stable and successful ladder climbing from the very beginning of our study, considering the total weight of the robot. So far, two methods have been applied to either absorb or compensate the position error caused by deformation, which are depicted in Fig. 8 as ② and ③. For the former, the hook structure on the end-effector to hang on the ladder rung is designed to be wider than the diameter of ladder rung so that there is a clearance and the error in X-axis within this range can be absorbed during ladder climbing [26], which is illustrated in Fig. 9. However, the effect of this method is very limited and the latter one of proximity

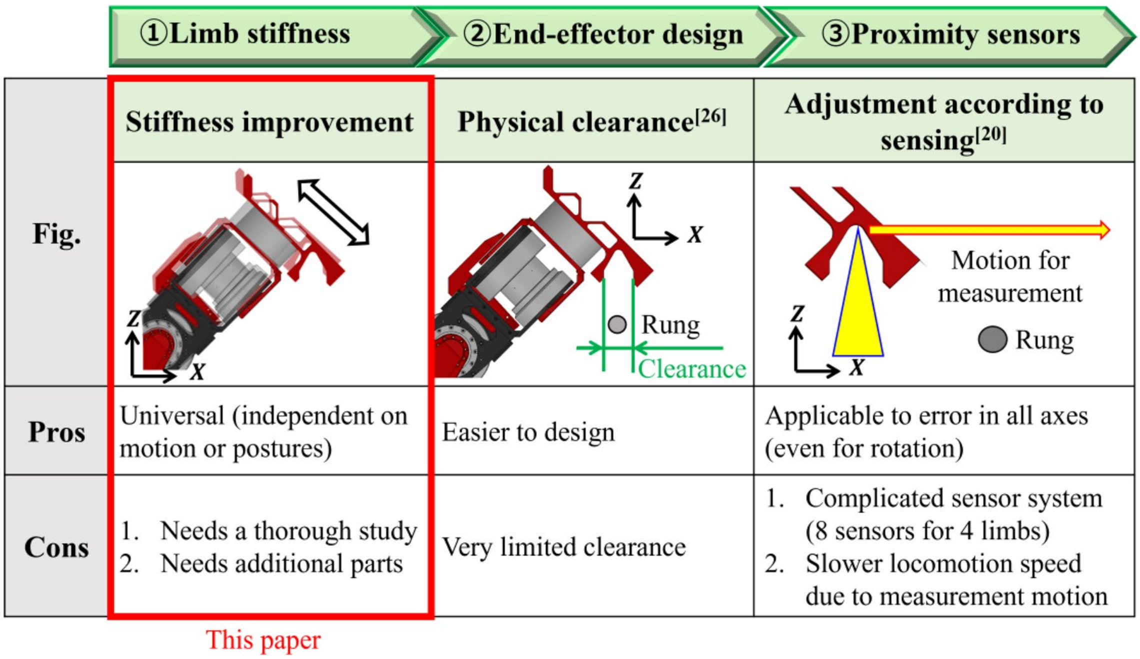


Fig. 8 Solutions proposed by the authors for the deformation

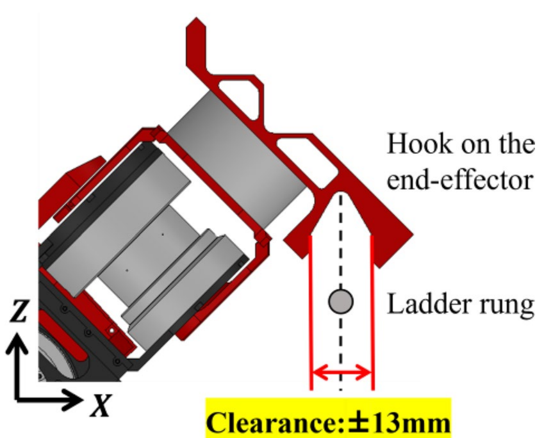


Fig. 9 Clearance of position error in X-axis for the hook on the end-effector

sensors are applied [20] as well. Sensors on the end-effectors can measure both the position and orientation of the target rung with the horizontal "scan" motion of end-effectors so that the motion of end-effectors can be adjusted according to the measured error. Viewing from the aspect of error compensation, proximity sensors and its corresponding motion adjustment is a perfect answer. Yet it is not from the aspect of climbing speed: the "scan" motion of end-effectors for measurement and the adjustment motion according to the measured error both takes extra time, which in our case is 12 s for one cycle of ladder climbing motion.

It is such a dilemma between error compensation and climbing speed that drives us to find a solution covering both of them: limb stiffness improvement depicted as ① in Fig. 8, a solution addressing the origin of deformation directly. Instead of adding proximity sensors, extra movement for maintaining stability or measurement of error due to deformation, redesign of mechanical parts reinforcing limb stiffness of the robot will be mainly discussed for the remaining part of this paper.

In this section, the details and analysis about the limb stiffness improvement are presented. First, the quantitative goal of stiffness improvement is determined in the form of end-effector position error. Meanwhile, other requirements in the hardware level are also given. Afterward, analysis about the distribution and amount of deformation for each link is given via experiments with motion capture and FEA is presented to further locate more detailed distribution of deformation in the target links for the specific design improvement of structural parts. Based on the goal, requirements and results of deformation distribution, the new design of parts is presented at last.

4.1 Requirements

Figure 7 and Fig. 9 show that the biggest position error of end-effector in X-axis due to deformation is 26 mm, and the clearance for that error is ± 13 mm, which means that the position error should be at least reduced to its half to guarantee successful ladder climbing in the proposed gait.

Besides the reduction of position error, the following points are also considered:

(1) Lightweight design with minimal change: the weight increased for each limb should be no heavier than 1 kg (approximately 3% of the total weight of 33 kg for one limb), which is verified in the former experiments that such an increase in weight is ignorable in end-effector position error;
(2) No influence on movable angle limit of each joint;
(3) No influence on the heat dissipation of motor drivers inside the joints;
(4) No influence on the space for circuit boards and wiring inside the joints.

4.2 Deformation Distribution Analysis: in a Limb

As is presented in Fig. 7, the deformation of the limb for WAREC-1R can be observed by the deformation of end-effector when an external force is exerted. However, this deformation is the sum effect of the deformation of all parts in the limb, and how much (ratio) they are accountable for this total deformation remains unclear. That is the reason why an experiment is made with the results shown in Fig. 10. Besides WAREC-1R, a copy of its one limb has been developed with all actuators, sensors and other parts just the same as WAREC-1R for evaluation experiments. In the experiments, a weight (approximately 200 N) is hung on the end-effector to create observable deformation. Meanwhile, markers for motion capture are attached to all links, and their change of position and orientation in 3D space are measured by the motion capture OptiTrack V120: Trio. Note that there are multiple markers attached to one link so that each link can be recognized as a whole instead of independent points by Motive, the software of motion capture. Joints are numbered as 1 to 7, starting from the base and links connecting them are therefore numbered as 1–2 to 6-Hook. Except for the 8% of deformation caused by the slip inside the joints that is difficult to eliminate, results show that 86% of the deformation in the white box of Fig. 10 is from link 1–2, 2–3, 3–4, 4–5 and 5–6, and only 6% is from the rest of links. Consequently, these 5 links are chosen to be the target of stiffness improvement in this paper.

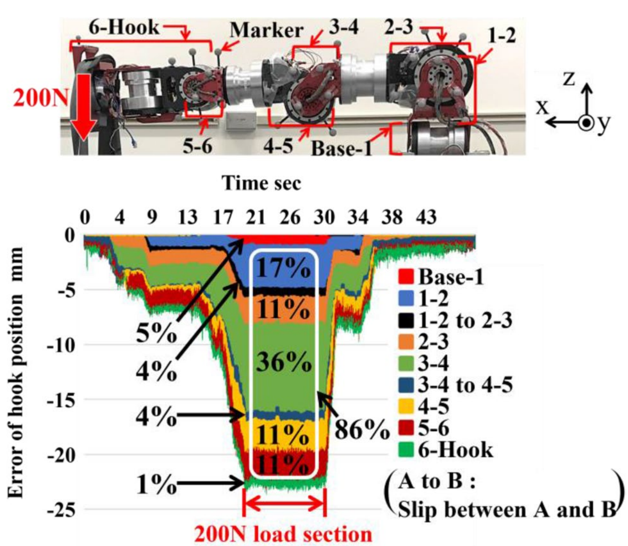


Fig. 10 Experiment with motion capture and its results

4.3 Deformation Distribution Analysis: in Links

For the optimization of the stiffness improvement with the minimal design change of parts, FEA in SolidWorks is performed to reveal the exact geometric deformation distribution in each link. Note that the condition of FEA is exactly the same as the experiment in Fig. 10. The results show that deformation concentrates relatively on the points connecting different parts with screws and the points with bigger curvature. Particularly, the points with both two features deform significantly.

Based on the results of FEA and with the consideration of point (1) – (4) describe in Sect. 4.1, improvements of (a) additional parts of plates and ribs attached to the deformation points and (b) design change of increasing thickness and adding support side plates are made, and all of them are made by 7075AA, the same material of WAREC-1R. Specifically, (i) for deformation focused on corner points, ribs are added; (ii) for deformation focused on two parallel lines, parallel support plates connecting them are added; (iii) for deformation on a whole plate, its thickness is increased and side support plate is also added if it is necessary and it does not influence the movable angle limit of the nearest joint. These improvements, ratio of deformation decrease as well as the weight increased due to the improvement for each part of the limb are illustrated and listed in Fig. 11 as a summary.

5 Experiment Results and Discussion

5.1 Experiment Results

With all new parts exchanged and whole-body motion planning verified, ladder climbing experiments in one rung skipping 3-point contact gait are performed to validate and evaluate the effect of limb stiffness improvement. All conditions and numerical results about the ladder climbing experiment are listed in Table 2 and snapshots of the experiments are presented in Fig. 12. Apparently, the ladder climbing with limb stiffness improvement is successful and its speed is about 67.5 m/h, which is approximately 28% faster than the former 2-point contact ladder climbing gait.

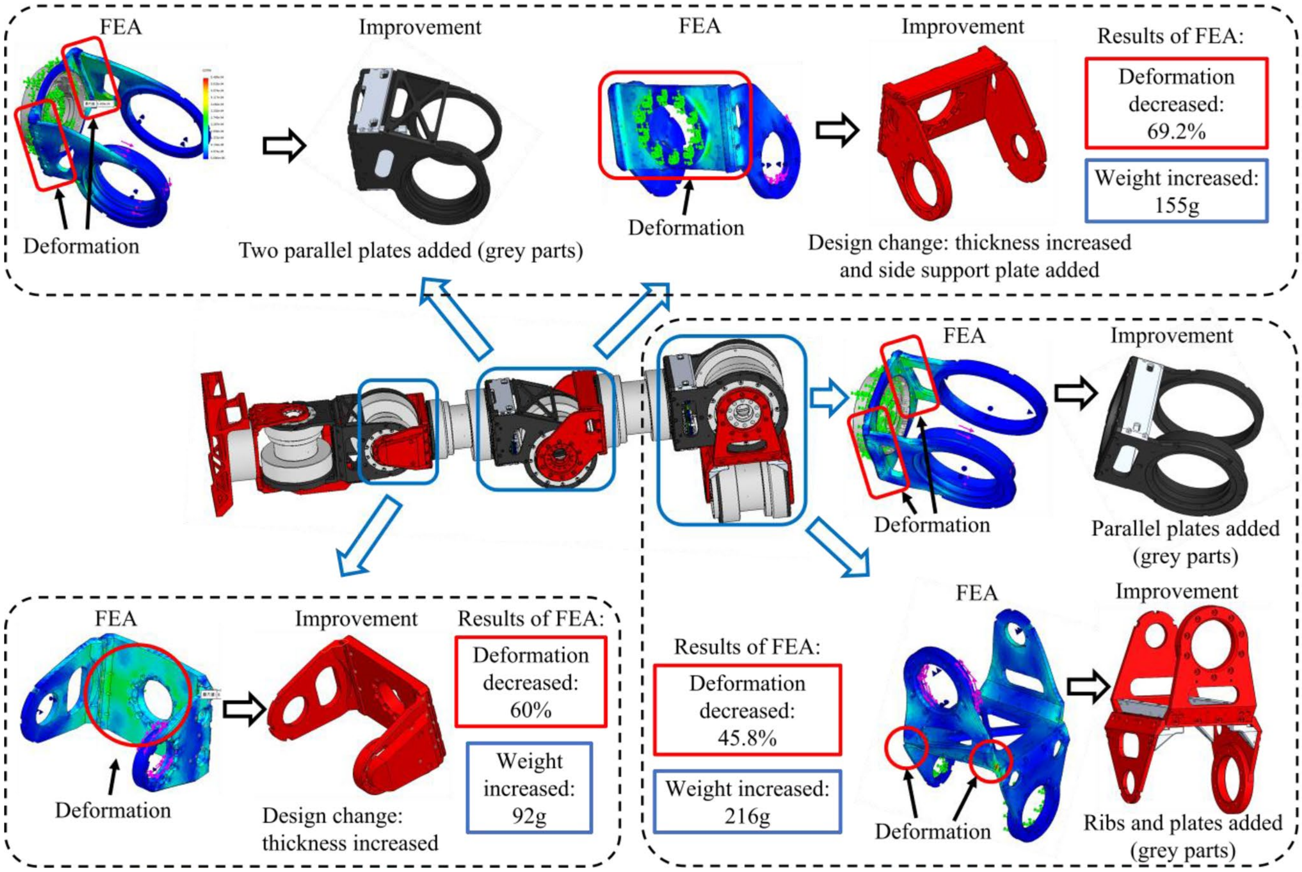


Fig. 11 Summary of the redesigned structural parts based on the results of FEA with estimated deformation decrease and weight increase

Table 2 Conditions and results of the ladder climbing experiments after the improvement

Term	Value/explanation
Ladder climbing gait	One rung skipping 3-point contact gait
Rung interval	300 mm
Pole distance	600 mm
Rung diameter	19 mm
Largest position error in X-axis	10.3 mm
Clearance of position error	± 13 mm
Time for one motion	8 s
Time for the whole cycle	32 s
Climbing speed	67.5 m/h
Mass increased for one limb	0.56 kg (1.7% up)
Total mass increased after the improvement	2.24 kg (1.3% up)

5.2 Discussion

The comparison of end-effector deformation in X-axis for ladder climbing before and after the limb stiffness improvement is presented in Fig. 13. The deformation decreases to 10.3 mm from 26.0 mm (60.4% down), which is very close to the estimated value of 9.9 mm in FEA, with the relative error of 3.9%. Since the decreased deformation in X-axis is also smaller than the clearance limit of 13 mm in Fig. 9, it has been proved that the limb stiffness improvement in this paper is valid in guaranteeing successful ladder climbing for the proposed new ladder climbing gait.

Meanwhile, the stability of the proposed climbing gait is also verified. CoM (Center of Mass) of the whole robot is estimated and it is projected on the ladder plane. Details of the CoM calculation can be seen in Ref. [21] and are omitted here. The position of CoM and the support polygon during a complete climbing cycle is depicted in Fig. 14 isometrically. Take support polygon of ① as example, its height is 1.8 m and its width is 0.4 m. It can be seen that CoM of the robot projected on the ladder plane is always inside the support polygon, verifying that the robot keeps stable throughout the whole climbing cycle.

Moreover, the influence of stability due to mass increase for one limb (0.56 kg, 1.7% of the total mass) is also analyzed. The max change of CoM during the whole cycle is 3.4 mm, which is much smaller than the smallest margin

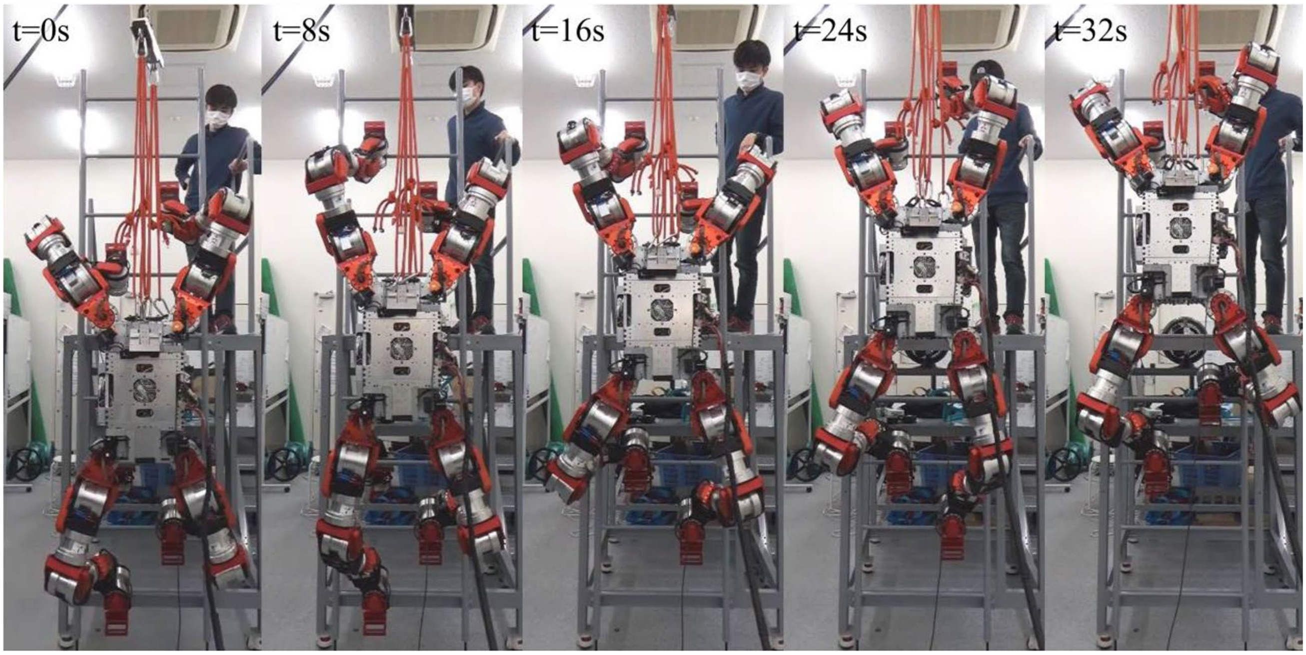
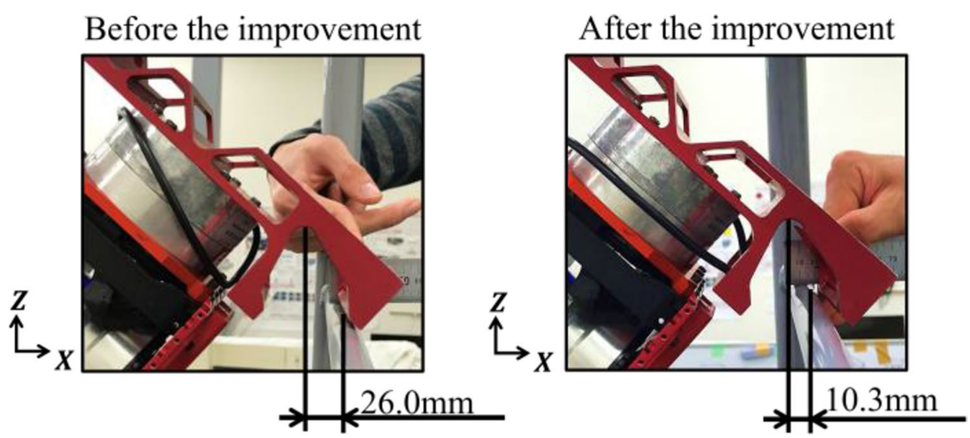


Fig. 12 Snapshots of ladder climbing in the new proposed gait

Fig. 13 Comparison of deformation before and after the limb stiffness improvement in ladder climbing



(103.2 mm), verifying that the mass increase of the robot has little influence on the stability of robot.

6 Conclusion and Future Works

This paper proposes a new gait for faster and stable ladder climbing as well as limb stiffness improvement of WAREC-1R to realize this climbing gait. The robot and its ladder climbing gaits are introduced, and its issue existing in ladder climbing due to the limb deformation is also described as the prerequisite knowledge. Subsequently, limb stiffness improvement by redesigning the parts where deformation is concentrated is explained as the key to realize the new proposed climbing gait. With the solution determined, deformation distribution in the limbs is measured through motion capture and exact geometric distribution of deformation in each link of limbs is also analyzed by FEA. Based on the former, target links for the stiffness improvement are determined and specific target locations for stiffness improvement are determined based on the latter. Considering the quantitative requirements of the decrease in end-effector position error as well as other hardware requirements besides the results of FEA, redesigned parts are made and exchanged. Finally, evaluation experiments of ladder climbing are performed. The results show that the proposed new ladder climbing gait is realized through limb stiffness improvement, with the deformation reduced to an acceptable value, which is very close to the estimated value in FEA. Meanwhile, the ladder

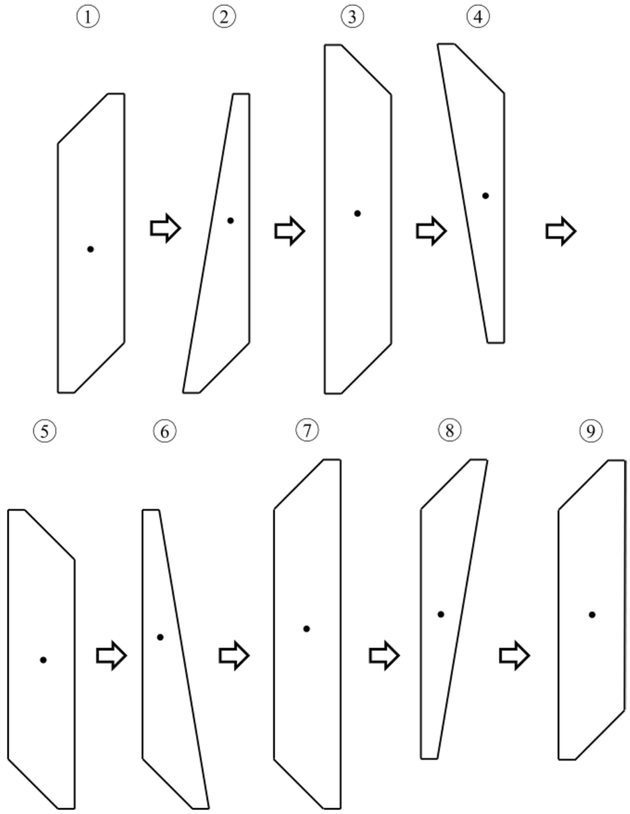


Fig. 14 Stability analysis: the relationship between the support polygon and CoM projected on the ladder plane (black point)

climbing speed is also 28% faster than the former 2-point contact ladder climbing, with better stability. Our future works include the verification of the improvement and its further application to other locomotion and manipulation tasks of WAREC-1R.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest concerning the publication of this manuscript.

References

1. Iida, H., Hozumi, H., & Nakayama, R. (1989). Development of ladder climbing robot LCR-1. *Journal of Robotics and Mechatronics, 1*, 311–316.
2. Yoneda, H., Sekiyama, K., Hasegawa, Y., & Fukuda, T. (2008). Vertical ladder climbing motion with posture control for multi-locomotion robot. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/SI.2009.5384556
3. Lu, Z., Aoyama, T., Yoneda, H., Sekiyama, K., Fukuda, T., & Hasegawa, Y. (2009). Vertical ladder climbing motion of pace gait with body motion control for a multi-locomotion robot. *Proceedings of the IEEE/SICE International Symposium on System*. https://doi.org/10.1109/SI.2009.5384556
4. Lu, Z., Sekiyama, K., Hasegawa, Y., Aoyama, T., Yoneda, H., & Fukuda, T. (2011). Climbing up motion of the multi-locomotion robot (MLR) on vertical ladder with different gaits. *International Journal of Mechatronics and Automation, 1*(3/4), 190–200.
5. Lu, Z., Sekiyama, K., Aoyama, T., Hasegawa, Y., Kobayashi, T., & Fukuda, T. (2012). Optimal control of energetically efficient ladder decent motion with internal stress adjustment using key joint method. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS.2012.6385887
6. Fujii, S., Inoue, K., Takubo, T., Mae, Y., & Arai, T. (2008) Ladder climbing control for limb mechanism robot "ASTERISK". In *Proceedings of the IEEE International Conference on Robotics and Automation*, Pasadena, CA, USA. https://doi.org/10.1109/ROBOT.2008.4543674
7. Saputra, A. A., Toda, Y., Takesue, N., & Kubota, N. (2019). A novel capabilities of quadruped robot moving through vertical ladder without handrail support. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS40897.2019.8968175
8. Takemori, T., Tanaka, M., & Matsuno, F. (2017) Gait design for a snake robot to climb a ladder. In *Proceedings of the International Symposium on Swarm Behavior and Bio-Inspired Robotics (SWARM2017)*, Kyoto, Japan, pp 89–92.
9. Takemori, T., Tanaka, M., & Matsuno, F. (2018). Ladder climbing with a snake robot. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS.2018.8594411
10. Luo, J., Zhang, Y., Hauser, K., Park, H., Paldhe, M., Lee, C., Grey, M., Stilman, M., Oh, J., Lee, J., Kim, I., & Oh, P. (2014) Robust ladder-climbing with a humanoid robot with application to the DARPA robotics challenge. In *Proceedings of the IEEE International Conference on Robotics and Automation*, Hong Kong, China. https://doi.org/10.1109/ICRA.2014.6907259
11. Feng, S., Whitman, E., Xinjilefu, X., & Atkeson, C. G. (2014). Optimization based full body control for the atlas robot. *Proceedings of IEEE-RAS International Conference on Humanoid Robots, 2014*, 120–127.
12. Vaillant, J., Kheddar, A., Audren, H., Keith, F., Brossette, S., Kaneko, K., Morisawa, M., Yoshida, E., & Kanehiro, F. (2014). Vertical ladder climbing by HRP-2 humanoid robot. *Proceedings of IEEE-RAS International Conference on Humanoid Robots*. https://doi.org/10.1109/HUMANOIDS.2014.7041435
13. Vaillant, J., Kheddar, A., Audren, H., Keith, F., Brossette, S., Escande, A., Bouyarmane, K., Kaneko, K., Morisawa, M., Gergondet, P., Yoshida, E., Kajita, S., & Kenehiro, F. (2016). Multi-contact vertical ladder climbing with an HRP-2 humanoid. *Autonomous Robots, 40*(3), 561–580.
14. Yoshiike, T., Kuroda, M., Ujino, R., Kaneko, H., Higuchi, H., Iwasaki, S., Kanemoto, Y., Asatani, M., & Koshiishi, T. (2017).

Development of experimental legged robot for inspection and disaster response in plants. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS.2017.8206364
15. Yoshiike, T., Kuroda, M., Ujino, R., Kanemoto, Y., Kaneko, H., Higuchi, H., Komuro, S., Iwasaki, S., Asatani, M., & Koshiishi, T. (2019). The experimental humanoid robot E2-DR: a design for inspection and disaster response in industrial environments. *IEEE Robotics & Automation Magazine, 26*(4), 46–58.
16. Hashimoto, K., Matsuzawa, T., Teramachi, T., Uryu, K., Sun, X., Hamamoto, S., Koizumi, A., & Takanishi, A. (2017). A four-limbed disaster-response robot having high mobility capabilities in extreme environments. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS.2017.8206436
17. Hashimoto, K., Kimura, S., Sakai, N., Hamamoto, S., Koizumi, A., Sun, X., Matsuzawa, T., Teramachi, T., Yoshida, Y., Imai, A., Kumagai, K., Matsubara, T., Yamaguchi, K., Ma, G., & Takanishi, A. (2017). WAREC-1—a four-limbed robot having high locomotion ability with versatility in locomotion styles. *Proceedings of the International Symposium on Safety, Security and Rescue Robotics*. https://doi.org/10.1109/SSRR.2017.8088159
18. Sun, X., Hashimoto, K., Hamamoto, S., Koizumi, A., Matsuzawa, T., Teramachi, T., & Takanishi, A. (2016). Trajectory generation for ladder climbing motion with separated path and time planning. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Daejeon, Korea*. https://doi.org/10.1109/IROS.2016.7759851
19. Sun, X., Hashimoto, K., Teramachi, T., Matsuzawa, T., Kimura, S., Sakai, N., Hayashi, S., Yoshida, Y., & Takanishi, A. (2017). Planning and control of stable ladder climbing motion for the four-limbed robot "WAREC-1." *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. https://doi.org/10.1109/IROS.2017.8206565
20. Sun, X., Hayashi, S., Hashimoto, K., Matsuzawa, T., Yoshida, Y., Sakai, N., Imai, A., Okawara, M., Kumagai, K., Matsubara, T., Yamaguchi, K., & Takanishi, A. (2018). Error compensation system with proximity sensors for vertical ladder climbing of the robot "WAREC-1." *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*. https://doi.org/10.1109/HUMANOIDS.2018.8625073
21. Sun, X., Hashimoto, K., Hayashi, S., Okawara, M., Matsuzawa, T., & Takanishi, A. (2021). Stable vertical ladder climbing with rung recognition for a four-limbed robot. *Journal of Bionic Engineering, 18*, 786–798.
22. Sun, X., Naito, H., Namiki, A., Liu, Y., Matsuzawa, T., & Takanishi, A. (2021). Assist system for remote manipulation of electric drills by the robot "WAREC-1R" using deep reinforcement learning. *Robotica, 40*(2), 1–12.
23. Matsuzawa, T., Hashimoto, K., Sun, X., Teramachi, T., Kimura, S., Sakai, N., Yoshida, Y., Imai, A., Kumagai, K., Matsubara, T., Yamaguchi, K., Tan, W., & Takanishi, A. (2017). Crawling gait generation method for four-limbed robot based on normalized energy stability margin. *Proceedings of the International Symposium on Safety Security and Rescue Robotics*. https://doi.org/10.1109/SSRR.2017.8088167
24. Matsuzawa, T., Koizumi, A., Hashimoto, K., Sun, X., Hamamoto, S., Teramachi, T., Sakai, N., Kimura, S., & Takanishi, A. (2020). Crawling and foot trajectory modification control for legged robot on uneven terrain. *International Journal of Mechatronics and Automation, 7*(1), 1–10.
25. Development of disaster response robot for extreme environment. Retrieved September 11, 2021, from http://www.takanishi.mech.waseda.ac.jp/top/research/rescue/system.htm
26. Matsuzawa, T., Hashimoto, K., Teramachi, T., Uryu, K., Sun, X., Hamamoto, S., Koizumi, A., & Takanishi, A. (2016). End-effector for disaster response robot with commonly structured limbs and experiment in climbing vertical ladder. In P. C. Vincenzo & S. Werner (Eds.), *ROMANSY 21-robot design dynamics and control.* Cham: Springer International Publishing.