

New Transmission Mechanism Technology Utilized in Prosthetic Legs

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ABSTRACT

The researchers developed a transmission mechanism that combines one-way clutches capable of rotating in both directions and can change speeds by switching the connection state of the clutch.

This makes the clutch smaller and lighter than an electromagnetic clutch and makes it possible to transmit driving force for both forward and reverse rotation. Other features of the mechanism are that it consumes power only for switching, not for maintaining the rotational state, and there is no limit to the number of speed ratio levels that can be set.

When this technology is applied to motor-driven prosthetic legs, the walking speed is independent of motor performance, which means that the motor can be made smaller and the prosthetic leg can be made lighter due to the power savings. In addition, the swinging of the leg while walking can be made quieter, which expands the life possibilities for users of prosthetic legs.

1. Development Background and Goals

1.1. Knee Joint Types and Functions

As Fig. 1 shows, there are various types of prosthetic legs, depending on the part of the body that is missing⁽¹⁾. Among these, a person without a natural knee joint uses a prosthetic leg with an artificial knee joint to replace the natural one.

These need to function similarly to the human knee. This includes supporting the weight of the body and flexing and extending the knee, among others. Among these, the role of missing muscles continues to evolve and can be replaced by various means.

The function introduced in this paper is primarily a knee joint yielding function using a damper⁽²⁾. The yielding function is the ability to flex the knee while applying moderate flexion resistance. This has become a major function of knee joints in recent years to help prevent unintentional sudden buckling of the knee when body weight is applied to the prosthetic leg and enable the user to go downstairs with natural alternating steps (Fig. 2). Recently, knee joints have become available that use a motor to replace the role of the muscles and flex and extend the knee. Both types of knee joints in recent years use knee angle sensors, load sensors, gyro sensors, and other sensors to detect the knee's status and operate dampers, motors, and

other devices.

Of these, damper-type knee joints with a yielding function have been the mainstream in recent years, but motor-driven knee joints are also expected to become more common in future.

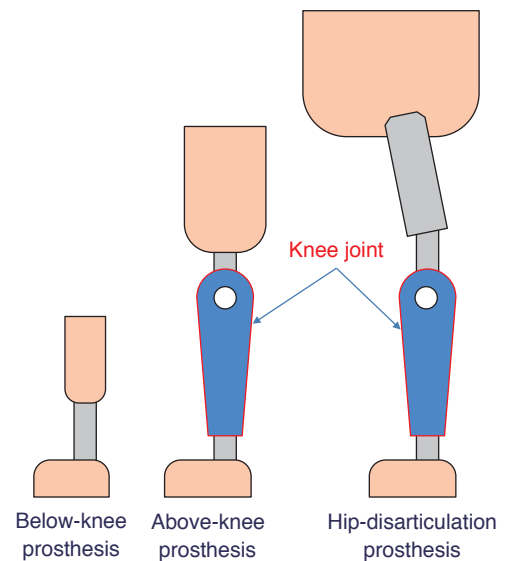


Fig. 1 Types of prosthetic leg

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1.2. Background to Development

Damper-type knee joints and motor-driven knee joints each have their strong points and issues.

In a damper-type knee joint, the damper provides an appropriate yielding function during the period when body weight is applied (the “stance phase”), which helps to prevent sudden buckling of the knee. During the period when no body weight is applied (the “swing phase”), the knee is passively flexed and extended in time with the swinging of the thigh. This allows the user to freely operate and walk, which makes the damper-type knee joint easy to handle. However, when the person is going upstairs, the knee joint does not exert force to extend the knee, so going upstairs with alternating steps of the two legs is not easy.

Motor-driven knee joints are driven by a motor in both the stance phase and swing phase. During the swing phase, the knee flexes and extends, which makes walking easier. During the stance phase, power from the motor makes it possible to perform movements that require power, such as going upstairs and standing up, which are not so easy with a damper-type knee joint. For that reason, the researchers believed that addressing the following three issues with motor-driven knee joints could make them easier to handle.

The first issue is that motor-driven knee joints consume considerable power because the knee joint is constantly being driven even while walking, which is how the knee joint is most frequently used. Therefore, the battery for driving the motor needs to have enough capacity for the frequency of use in daily life. This could increase the size and mass of the battery. Secondly, the motor is constantly driving the knee joint while walking, so there is motor drive noise at all times. Thirdly, the speed while walking depends on motor performance. This is because the speed of flexion and extension of swinging increases as walking speed increases. Another factor is that the motor needs to be larger to operate without being restricted by the walking cadence

Table 1 Issues addressed by this research

No.	Issue
1	Power saving while walking on level ground (battery downsizing)
2	Reduction of motor drive noise while walking on level ground
3	Walking cadence independent of motor performance (motor downsizing)

(the number of steps per minute).

In this paper, to address the three issues listed in Table 1 and below, based on a motor-driven knee joint, the researchers developed not an entire prosthetic leg system but a transmission, which is a technical element of such a system.

- Power saving while walking on level ground (battery downsizing)
- Reduction of motor drive noise while walking on level ground
- Walking cadence while walking on level ground independent of motor performance (motor downsizing)

2. Goals

2.1. Ideal Behavior of Knee Joints

The greatest advantage of motor-driven knee joints is their potential to expand the range of the user’s mobility and activity, for example by enabling them to go upstairs. The researchers believed that this advantage could be used to help realize Honda’s 2030 Vision, which is to “Serve people worldwide with the ‘joy of expanding their life’s potential’⁽³⁾.”

When the user is going upstairs, it is necessary to provide force for the knee joint to extend. By contrast, movements such as walking on level ground do not require power. The researchers believed an effective way to address issues 1–3 in Table 1 would be to aim for behavior similar to that of a damper-type knee joint without providing power.

First, the researchers separately considered walking on level ground and going upstairs, based on whether there is a need to provide extension force to the knee joint.

For walking on level ground, as previously mentioned, the aim was movements like those shown in Fig. 3, which refers to the ease of handling of the damper-type knee joint and the sense of assurance with the yielding. Specifically, during the swing phase, the connection between the motor and the knee axis is cut to allow free rotation of the knee axis so that the user can freely handle the prosthetic leg. During the stance phase, the knee axis is connected to the motor to provide flexion resistance by yielding. The back drive torque of the motor is used as the flexion resistance at this time. As a result, the only power required when walking on level ground is for the switching operation, thereby saving power. In addition, as the knee axis is not connected to the motor during the swing phase, this can help

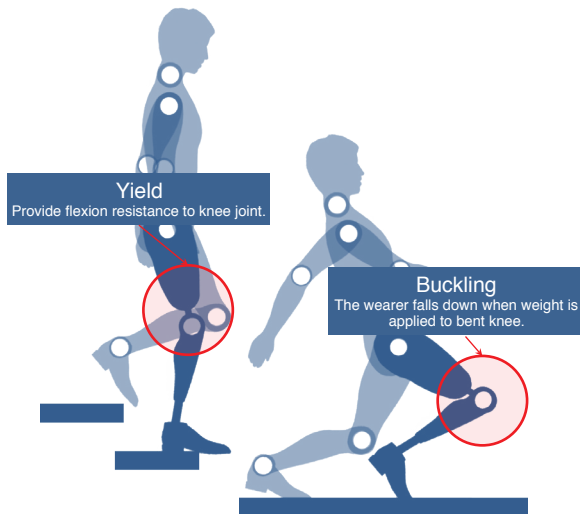


Fig. 2 Yielding and buckling

prevent motor noise. Moreover, the flexion and extension movements are not motor driven during the swing phase, and thus in this concept, walking speed is not limited and all three of the issues listed in Table 1 can be achieved. The motor provides the yielding function, and thus development can aim for a sense of assurance and ease of handling equivalent to those of a damper-type knee joint.

Next, for going upstairs, the motor's driving force is used for extension and flexion of the knee axis, aiming for movements such as those shown in Fig. 4.

Specifically, during the stance phase, the motor forcefully extends the knee to support the body weight. During the swing phase, the motor quickly flexes the knee to help avoid differences in level.

The speed ratio between stance and swing at this time was set to approximately 1:2. The reason is that, in the human gait, the flexion movement of the swing phase is about twice as fast as that of the stance phase, as shown in Fig. 5⁽⁴⁾.

In addition, the knee joint needs to be capable of both extension and flexion movements during both the stance phase and swing phase.

2.2. Functional Requirements and Limiting Conditions

To achieve the goals laid out in Section 2.1., the following functional requirements and limiting conditions were set for knee joints.

(1) Functional requirements

While walking on level ground:

During the swing phase, the transmission shall be in

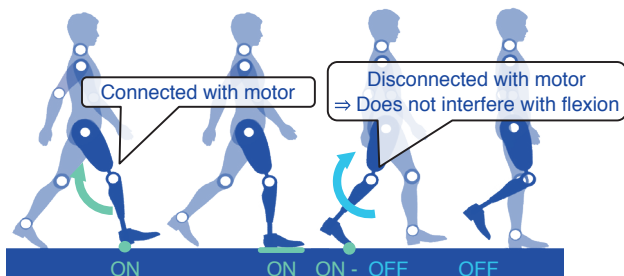


Fig. 3 Aim of walking on level ground and going downstairs

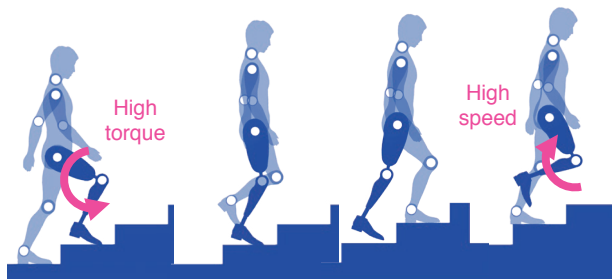


Fig. 4 Aim of going upstairs

neutral state and the user shall be able to rotate the knee axis freely.

During the stance phase, the knee axis shall be connected to the motor and the user shall be able to apply resistance to the knee axis. In addition, the switch from free rotation to yielding shall be instantaneous.

Power shall be consumed only for the switching operation.

When going upstairs:

It shall be possible to connect to the motor at two speed ratios, and the user shall be able to get assist power while high torque is being output during the stance phase and high rotation speed during the swing phase.

The knee joint shall be able to provide driving force in both the extension and flexion directions of the knee axis.

(2) Limiting conditions

The device shall be small enough to fit within the silhouette of the knee.

As it was considered necessary technology for achieving the above functional requirements and limiting conditions, a compact transmission technology was developed that can instantly switch the connection state with the motor between neutral and two speed ratio levels in synchronization with the state transition between the stance phase and swing phase.

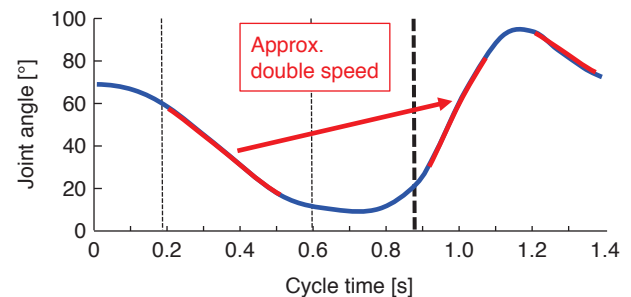


Fig. 5 Speed difference between stance phase and swing phase when going upstairs

3. Basic Structure of Transmission

3.1. Overall Structure of Transmission

The overall structure of the transmission and the names of the transmission's main functional parts are shown in Figs. 6 and 7, respectively.

Three parts, the gear, shaft, and roller, transmit the power. Whether or not power is transmitted between the gear and shaft changes depending on whether the roller is engaged between the shaft and gear. The retainer holds the roller in position. Gears A and B each have a different number of teeth, etc., based on the speed ratio, but the structure on the inside is the same.

To switch the state of power transmission, the rod actuator operates, making the rod move up and down via

a rack-and-pinion mechanism. The rod is cam-shaped, and the cam moves the pin. The pin pushes the pin guide, which moves the retainer and changes the status of the roller.

Grease is applied inside the shaft and to the sliding parts of the clutch.

Figure 7(a) shows the rod in axial cross section. The connection state of gears A and B changes as the rod in the shaft slides along the shaft axis. The rod has two cam shapes, one with a large diameter and one with a small diameter. The clutch is OFF when the part with the large diameter is positioned in the center of gears A and B, and ON when the part with the small diameter is positioned there. Details are provided in Sections 3.2. and 3.3. The motor and rack-and-pinion mechanism shown in the lower part of Fig. 7(a) make the rod slide. The back drive torque of the motor holds the rod's position.

3.2. Switching Clutch from OFF to ON

The state transition during switching is shown in Fig. 8. This section focuses on the change in gear B. Parts of Fig. 8 are shown in enlarged form or in cross section in Figs. 9, 10, and 11.

When the rod is slid downwards from the clutch OFF state, the state of contact between the pin and rod changes and a gap is created (Fig. 9). As Fig. 10 shows, when

rotational force is applied to the gear at this time, the retainer rotates while the pin is pushed back by the cam of the pin guide. During this process, the gear and retainer co-rotate due to friction of the grease that was applied between them. The roller is sandwiched between the gear and shaft and transmits rotational force to the shaft (Fig. 11). Torque is transmitted by this type of mechanism. Moreover, because the gear and retainer co-rotate, even if the gear reverses, the roller is sandwiched again, on the opposite side of the shaft, and rotational force is transmitted to the shaft.

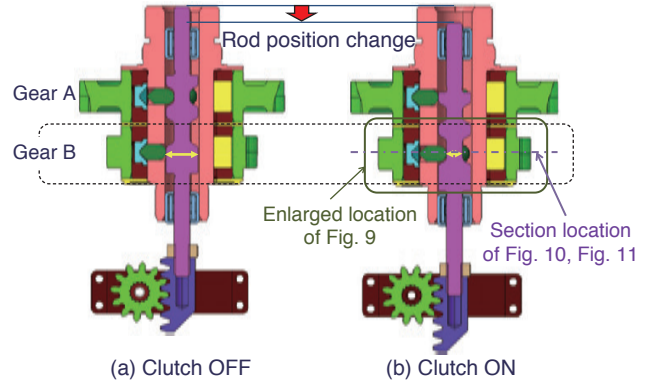


Fig. 8 Switching clutch from OFF to ON

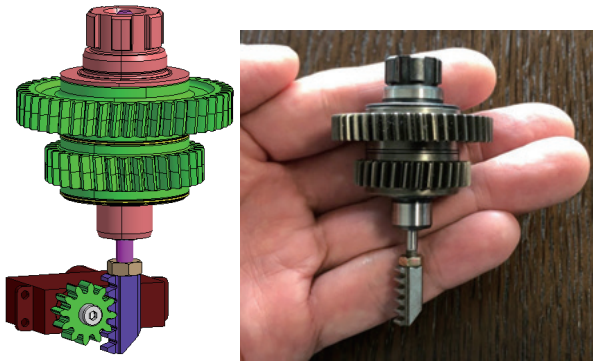


Fig. 6 Overall structure of transmission

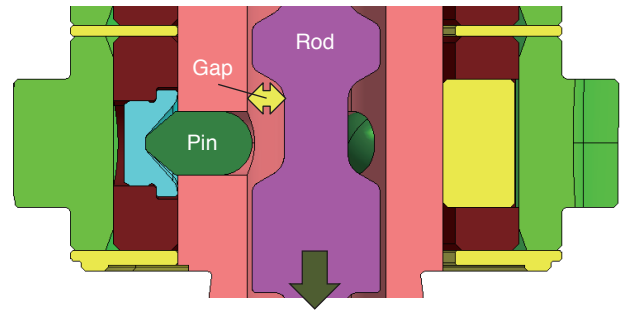


Fig. 9 Rod state when switching clutch from OFF to ON

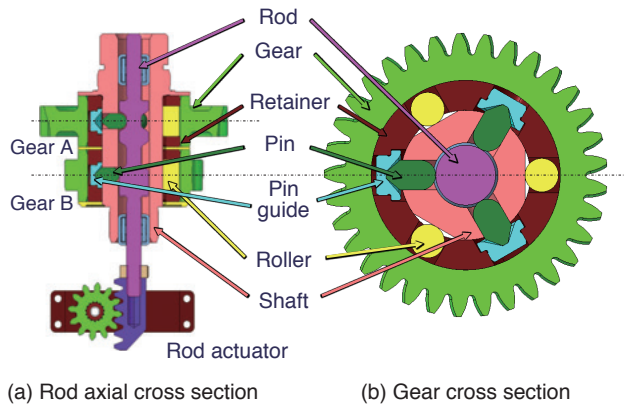


Fig. 7 Structure of transmission

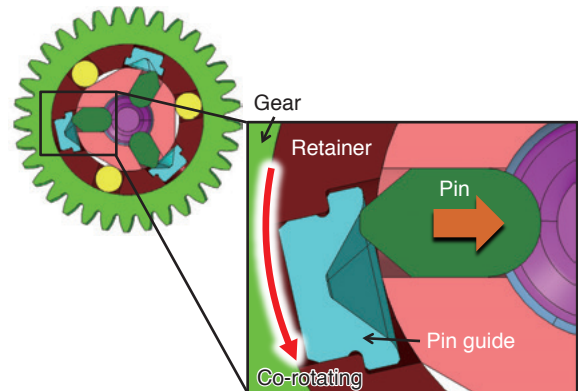


Fig. 10 Pin state when switching clutch from OFF to ON

3.3. Switching Clutch from ON to OFF

When the rod is slid upwards again from the clutch ON state, the pin is pushed outward by the cam on the rod (Fig. 12). During this process, the pin pushes up the pin guide and the retainer and roller are fixed in place (Fig. 13). In that position, the gear and shaft do not come into contact with the roller at the same time, and thus there is idling (Fig. 14).

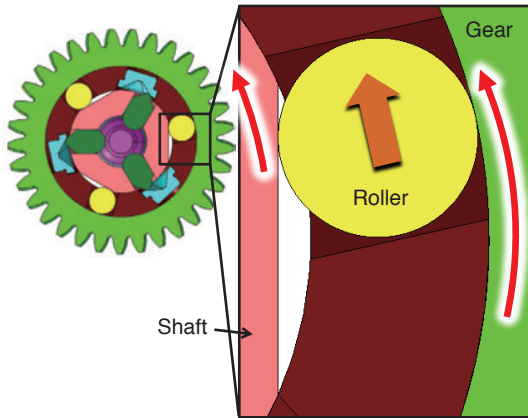


Fig. 11 Roller state when switching clutch from OFF to ON

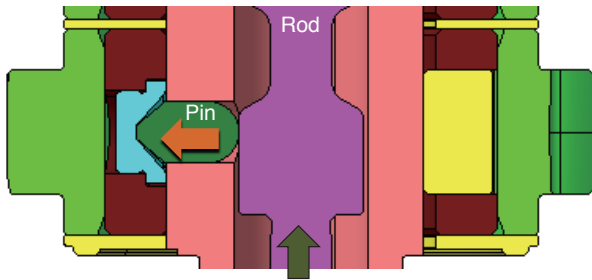


Fig. 12 Rod and pin state when switching clutch from ON to OFF

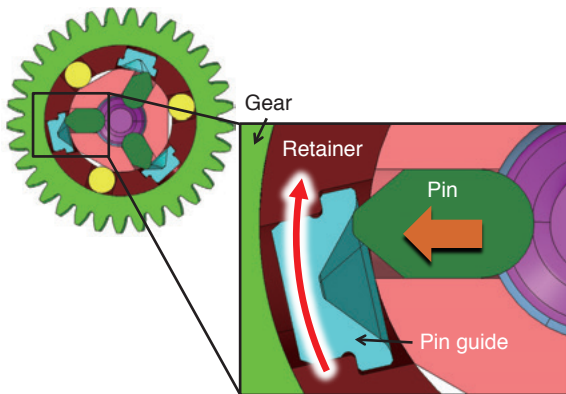


Fig. 13 Pin and retainer state when switching clutch from ON to OFF

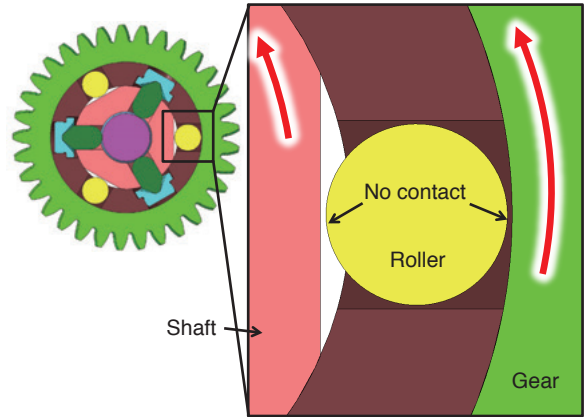


Fig. 14 Roller state when switching clutch from ON to OFF

4. Operation in a Prosthetic Leg

4.1. Incorporation into a Prosthetic Leg

Figure 15 shows an example of the system structure when the transmission is incorporated into a prosthetic leg. Figure 16 shows an example of how the mechanical components are structured. Torque from the motor enters the knee joint via the transmission. The torque exerted by the person from the knee joint side also enters the motor via the transmission in the same way. In this structure, three sensors measure the state of the knee. A load sensor measures the loading and unloading of body weight. An IMU sensor measures the stance of the knee joint. The knee angle sensor measures the angle between the thigh and lower leg components.

4.2. Operation in a Prosthetic Leg

The transmission is made to operate in a prosthetic leg

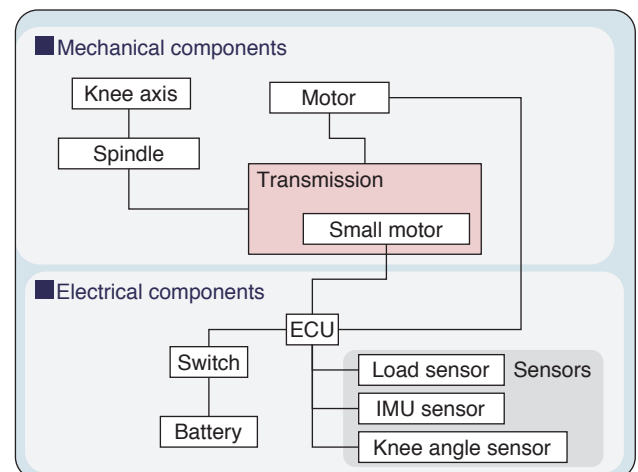


Fig. 15 System structure of knee joint

as shown in Figs. 17 and 18.

For the swing phase of walking on level ground, both gears are set to neutral, as shown in Fig. 17(a). This is the clutch OFF state for both gear A and gear B. Free flexion and extension movements, due to the swinging of the user's thigh, are possible.

For the stance phase, gear A is set to clutch OFF and gear B (the high rotation gear) is set to clutch ON, as shown in Fig. 17(b). The rotation of the knee joint is transmitted to the motor, and proper yielding is made to function by utilizing the back drive torque of the motor. This can help to prevent unintentional sudden buckling of the knee during the stance phase and give a sense of assurance to the user.

Next, this section discusses going upstairs. During the stance phase, high torque is required to support the user's body weight, but the rotational speed is slow. However, flexion and extension during the swing phase require only below-knee inertial force, which means that the high torque is not necessary, but a high rotational speed is required. The transmission mechanism with two gear ratios effectively addresses these conflicting requirements.

For the swing phase, the clutch for gear B (the high rotation gear) is set to ON and the clutch for gear A is set to OFF, as shown in Fig. 18(a). Using the motor to flex and extend the knee joint at high speed enables the user to step onto the next step without touching the staircase risers.

For the stance phase, the clutch for gear A (the high-torque gear) is set to ON and the clutch for gear B is set to OFF, as shown in Fig. 18(b). The output of the motor is transmitted to the knee joint with high torque to assist knee

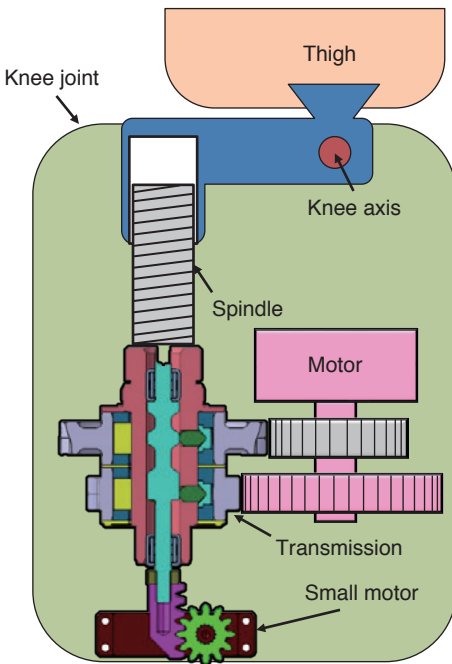


Fig. 16 Mechanical system structure of knee joint without electrical parts

Table 2 Phases, modes, and their goals

Situation	Phase	Transmission mode	Aim
Walking on level ground/going downstairs	Swing	Neutral	Easy to handle
	Stance	High speed	Yielding
Going upstairs	Swing	High speed	Avoid steps
	Stance	High torque	Lift weight

extension, enabling the user to go upstairs.

Table 2 summarizes the above transmission modes and their goals during the walking cycle.

4.3. Check of Operation When Used in a Prosthetic Leg

Log data of walking on level ground is shown in Fig. 19. A force sensor and IMU sensor mounted on the prosthetic leg are used to determine whether the knee joint is in the stance phase or swing phase. During the stance phase, the rod position switches to the high torque mode before load is applied, which enables the resistance of the motor to help prevent buckling of the knee. In the swing phase, moreover, the transmission switches to neutral before the knee angle increases. It was confirmed that, as a result,

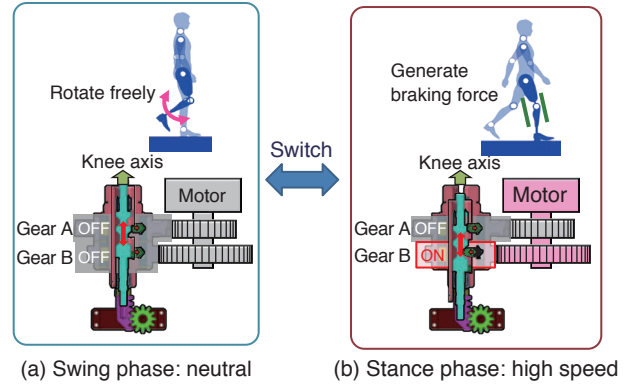


Fig. 17 Transmission switching when walking on level ground or going downstairs

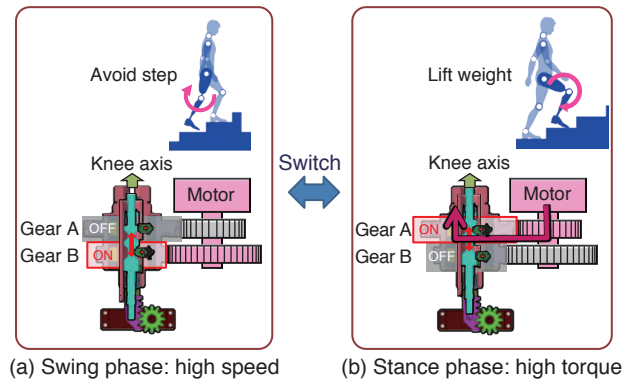


Fig. 18 Transmission switching when going upstairs

the knee angle can be flexed quickly without interference from the motor's resistance.

Log data of going upstairs is shown in Fig. 20. While the user is going upstairs, the force sensor determines whether body weight is being applied to the prosthetic leg, and based on that, switches between the stance phase and the swing phase. The numbers for load (shown in light blue) show how load changes with body weight. They show that when no body weight is applied, the rod position switches from the stance phase to the swing phase, and when body weight is applied, it switches from the swing phase to the stance phase.

4.4. Summary of Issues, Countermeasures, and Results for Motor-Driven Knee Joints

Table 3 summarizes countermeasures and results for the three issues previously listed in Table 1.

Regarding the first issue, power saving while walking on level ground (which accounts for much of the time the prosthetic leg is in use) and downsizing the battery, the transmission lowered power consumption by going into a neutral state during the swing phase. Even yielding using the back drive torque of the motor during the stance phase does not consume power. As power is consumed only during switching and only to move the rod up and down, the capacity of the onboard battery can be reduced. Another advantage is that this transmission does not consume power to maintain either state, as friction-type clutches do.

Regarding the second issue, reducing motor drive noise

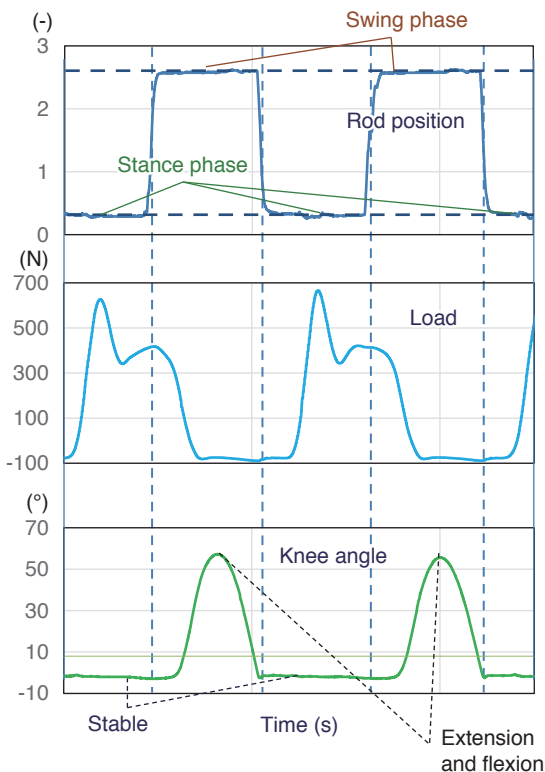


Fig. 19 Log data of walking on level ground

Table 3 Issues addressed, countermeasures, and results of this research

No.	Issue	Countermeasure	Result
1	Power saving while walking on level ground (battery downsizing)	During the swing phase while walking on level ground, do not	Power consumption only for switching, except for activities that require power (e.g. going upstairs)
2	Reduction of motor drive noise while walking on level ground	perform extension and flexion by the motor, only switch the state of the knee joint.	No motor noise except for activities that require power (e.g. going upstairs)
3	Walking speed independent of motor performance (motor downsizing)		Walking speed independent of motor performance because knees are not moved by motors during walking

while walking on level ground, when this transmission is used, no noise is generated because there is no connection with the motor during the swing phase. During the stance phase, noise is generated because of the connection to the motor in situations where yielding is used. However, when walking on level ground, yielding is only used when the user starts to fall and the knee buckles, and basically there is no noise during the stance phase as well. During switching, the small motor used for switching makes very little noise, about the same as other electronically controlled knee joints. The above indicates that a structure and control have been realized that do not generate operating noise when walking on level ground.

The third issue is that the walking speed should be independent of motor performance. This is so that the neutral function of the transmission will allow it to be moved by the user's stump (the part of the thigh remaining after amputation), like a damper-type knee joint.

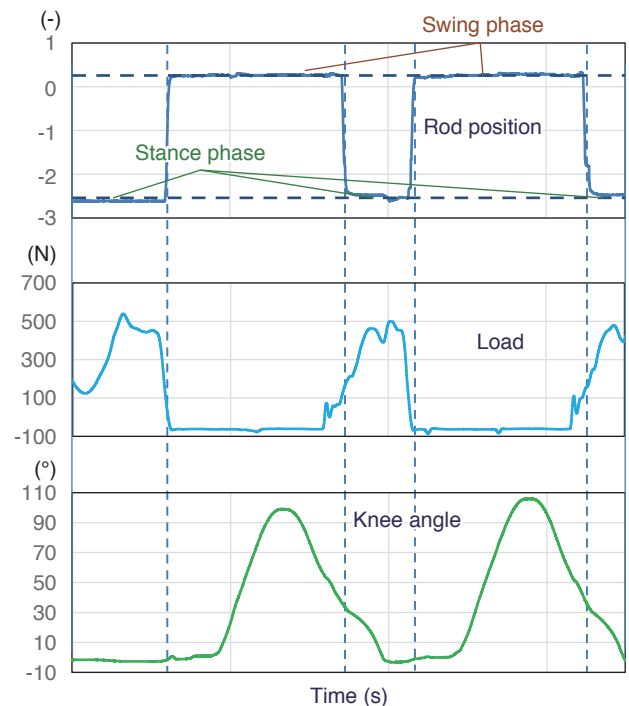


Fig. 20 Log data of going upstairs

Table 4 Performance comparison of roller friction and electromagnetic clutch

Features	Roller friction type	Electromagnetic clutch type		
		Company A	Company B	Company C
Outside shape (mm)	$\phi 25$	$\phi 106$	$\phi 75$	$\phi 90$
Mass (kg)	0.2	1.5	1	1
Static friction torque (N·m)	15-20			

In addition to addressing the three issues above, the following functions can be added when applying this technology to prosthetic legs.

- The prosthetic leg is easy to handle, with ability to walk freely on level ground.

By setting the roller clutch connection state in both gears to neutral, the lower leg can be swung out by the user's thigh. The user can walk freely without any restrictions on walking speed or cadence.

- The ability to provide bidirectional rotary drive encourages a sense of assurance for the user.

Because rotary driving force can be transmitted in both directions, it is possible to drive in opposite directions, such as flexion and extension, without switching. This encourages a sense of assurance for the user. The reason is that the knee joint can continue to support the body weight without fear that the clutch will disengage, even if the rotation unexpectedly goes the opposite direction.

- It is possible to switch between multiple reduction ratios.

The knee joint can have multiple reduction ratios, and different output characteristics can be achieved with a single motor, so that the knee joint can provide optimal characteristics during the stance and swing phases. Finding points for greater efficiency, and adjusting the amount of current are expected to contribute to the downsizing of motors and batteries.

4.5. Advantages over Electromagnetic Clutches

Table 4 lays out the characteristics of compactness and light weight that the new technology achieved compared to electromagnetic clutches. The results suggest that the technology could be effectively used not only for prosthetic legs but also for other products.

5. Conclusion

This development started with the goal of developing elemental technology to take advantage of the merits of motorized knee joints, and a prototype knee joint incorporating a new transmission mechanism was confirmed.

When the user is walking on level ground, the motor is not connected during the swing phase, but rather is connected during the stance phase. Power is saved because power is only consumed for switching. In addition, during the swing phase, there is no connection with the motor, which enables walking with less noise. Moreover, the mechanism can be disconnected from the motor and moved

by the thigh, making it possible to walk without depending on motor performance.

During the stance phase, yielding functions similarly to a damper-type knee joint, enabling the user to walk with a sense of assurance.

Also, when going upstairs, the speed ratio can be switched according to the characteristics required for the stance phase and swing phase, which helps to make the motor smaller.

This transmission has many merits compared to electromagnetic clutches, including a compact and lightweight mechanism that can transmit torque, the ability to provide bidirectional rotary drive, no limit to the number of speed ratios, and no power consumption to maintain the state during torque transmission. As such, it is an effective means for achieving the objectives of a knee joint in a prosthetic leg.

As the features of this technology are expected to function effectively in other devices, the researchers hope it will be used in devices that can take advantage of its unique merits.

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