Development of a torque limiter for the gear of an assistive walking device

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Abstract
Wearable assistive devices have been receiving considerable attention in academic circles. To make these devices efficient, we need additional research on the service lives of the mechanical elements used in these devices. The wearers of these devices frequently encounter unexpected movements that lead to motor failure in the devices. The purpose of this study is to develop an overload protection mechanism using a torque limiter, which can eliminate the overload torque delivered in the reverse direction to effectively prevent the device from breaking and ensure the safety of the user. To improve the service life of assistive walking devices, we designed a sandwich mechanism for the final gear of the servo motor. We made the material from rubber and configured it between a pair of circular plates. The surface tractive force delivered the required torque. When the surface load exceeded the maximum friction force, the circular plates slipped and protected the device. In this paper, we implement a torque limiter and prove its durability by performing experiments using two circular plate designs, one with grooves type and another without grooves type. We also use various materials to assess the applicability of the assistive walking device. The findings indicate that the with grooves type gives better torque performance; it achieves the same rated torque as the servo motor. Thus, this study recommends that with grooves type is particularly suitable for the elderly who require high assistive power. On the other hand, without grooves type is suitable for users who employ the device for extended periods because this type has an excellent service life. Our experiment proves that the torque limiter that we developed can withstand the load torque over 300 times for situations involving the loss of balance such as stumbling and slipping. Finally, we experimentally validate the improvement of walking performance by using this torque limiter.

Keywords: Overload protection mechanism, Torque limiter, Walking assistance, Delivered torque, Durability

1. Introduction

With an increase in the aging population worldwide, diseases, such as apoplexy, have also increased leading to a corresponding increase in the demand for wearable assistive devices. Aging causes a decrease in the muscle strength, which leads to decreased physical activity. To address this issue, the elderly must maintain good health and regain their independence even after being struck by illnesses that weaken the musculoskeletal system. Over the past few years, a number of studies have been conducted on developing mobility aids for humans. Several studies have designed assistive walking devices (Sankai, 2010) that focus on the hip joint and/or the knee joint to help in walking. For instance, Blaya et al. (2004) concentrated on treating drop-foot gait; they proposed the Active Ankle-Foot Orthosis. Guizzo et al. (2005)
investigated ways for supporting the elderly and people with disabilities by using an exoskeleton to walk, climb stairs, and carry things around. Saglia et al. (2009) used a rehabilitation robot to enable the ankle to perform plantar/dorsiflexion and inversion/eversion by using a parallel mechanism. Sankai (2010) developed an assistive device for people who suffered from muscular weakness. ReWalk™ (Esquenazi, 2012) aimed to help people who suffered from serious spinal cord injuries to regain their activities of daily living. Sanz-Merodio et al. (2014) developed lower-limb exoskeletons that helped paralyzed children walk. The tibialis anterior muscle is the muscle that is most prone to fatigue during human walking. Consequently, we have developed various assistive devices that focus on assisting the ankle joint during the walking movement. Using our designed aid devices designed, the equipped foot can be raised automatically through the neural pathway of human stretch reflex. Our findings confirmed that our device could effectively improve the gait of the user (Tanaka et al., 2015a, 2015b). This walking assistance device had two modes: an all-round mode and a walking mode. It is suitable for able-bodied people and hemiplegic patients. To diminish the burden on the wearer, we needed to reduce the weight, downsize, and improve the usability of this assistive device. Thus, we developed a new, small, low-cost, and simplified walking assistance device that uses microcomputers in conjunction with servo motors. In the field of human rehabilitation engineering, many researchers have focused on developing assistive devices to serve apoplexy patients and the elderly. However, when these devices were tested by users in an outdoor environment, the service life of the mechanical components of the assistive device diminished substantially. In real life, the wearer of the assistive device often experiences unpredictable movements, which frequently cause the gear transmission of the servo motor to break down. Therefore, it became necessary to develop a torque limiter mechanism that could protect the motor against the inverse input of the overload torque.

The aim of this paper is to develop an overload protection mechanism using a torque limiter mechanism to prevent the breakage of walking assistance devices. In this study, we used the sandwich design as the torque mechanism to improve the service life of the walking assistance device. To determine the delivered torque, we designed two types of circular plates, one with grooves and another without grooves, using nitrile-butadiene rubber (NBR) and polyvinylchloride (PVC). In this study, we obtained the S–N curve to evaluate the durability of the two torque limiter designs that used two materials. The results proved that the torque limiter could be successfully used for human rehabilitation engineering because of its overload protection mechanism.

2. Walking Assistance Device

In our earlier study (Tanaka et al., 2016), we developed a device that consists of a flexible shaft and a worm gear, which made the device quite heavy for the wearer (5.6 [kg]). Therefore, we designed a new assistive device for neuro-rehabilitation and the promotion of exercise, as shown in Fig. 1. This device is small, lightweight (1.6 [kg]), and low cost (Tanaka et al., 2016). For this assistive walking device, we used the angle control method to control the servo motor. Then, based on the situation of the wearer, we fine-tuned the target angles for each leg. We used the Arduino microcomputer, Arduino I/O ports, and the servo motor for the control system; this was simple and cost-effective. In this case, the assistive device’s structure had only a single frame attached on the outside of the leg; thus, the ankle joint enabled the relative rotation of the internal and external frames. We attached a pressure sensor to the sole of the device so that we could determine the contact state between the sole and the ground and recognize the locomotion phase of the human. This assistive device includes two actuation modes (the all-round mode and the walk mode); these modes were dedicated to easily perform the activities of daily living. The all-round mode focused on all the motions that involved walking, getting up, sitting, and standing. Then, the walk mode was used to teach and guide the user to correct his/her gait during walking. Using the assistance of only the ankle joint, this assistive walking device produced a stretch reflex in the bi-articular muscle of the user; thus, the user’s leg could be raised. By using monosynaptic reflexes of humans, the user did not need to be equipped with the actuator on the knee joint. Therefore, the muscle burden of the user’s leg could be drastically decreased (Tanaka et al., 2016). The device that we designed could be worn very easily and quickly on the human feet while wearing shoes. However, the servo motor used aluminum of the transmission gear material to take measurements against the overload, and this design easily destroyed the gear teeth. Therefore, in this study, we developed a torque limiter mechanism in the servo motor, which not only prevents the breaking of the transmission gear from overload but also ensures the safety of the user.
3. Development of a Torque Limiter
3.1 Torque Limiter Mechanism

We developed a torque limiter and incorporated it in the final gear to effectively prevent gear breakage in assistive walking devices. This device employed the servo motor KONDO-B3M-SC-1170-A, which was lightweight (105 [g]) and had small dimensions (51 × 32 × 39.5 [mm]). This servo motor had a maximum torque of \( T = 7.6 \) [N-m], a rated torque of \( T = 4 \) [N-m], a maximum actuation of \( \pm 320^\circ \), and a high reduction ratio of \( 382.88:1 \) (KONDO, 2017). Furthermore, the servo motor could use two control methods: position control and angular velocity control. During the development of the assistive walking device, we found that the final gear of the servo motor broke frequently when the subjects tried it out. As in a real-life situation, the user regularly encountered unforeseen movements, which caused an unexpected input of an inverse torque in the gear box of the servo motor. This broke the gear teeth, as shown in Fig 2. We developed a torque limiter to prevent damaging the gear box and maintain the user’s safety. To use the wearable assistive device, it had to be placed directly on the human body. Therefore, we developed the torque limiter because safety issues were a major concern. We used the sandwich mechanism for the torque limiter, which consisted mainly of three parts: 1) the final gear, 2) the output shaft, and 3) the hollow rubber circular plate. Figure 3 shows the schematic of the torque limiter mechanism. The configuration of the torque limiter is such that the hollow rubber circular plate is arranged between the final gear and the output shaft. The torque limiter mechanism was assembled into the servo motor to work as an overload protection system for the assistive walking device. When using the torque limiter, the output shaft would be subject to an axial thrust that would generate a friction force on the circular rubber plate; this will then drive the rotation torque. This study aimed to develop a lightweight and small-dimensional assistive walking device; therefore, we selected a small motor at the start of the development. However, the gear of the servo motor broke frequently during the practical trials; therefore, we modified the gear of the servo motor. In our design, this torque limiter had the same size and weight as the unmodified gear. Using this design, the servo motor could maintain the volume and weight consistently with the original motor. Hence, we did not need to use an additional commercial torque limiter for this assistive walking device. By using this torque limiter design, we could eliminate the inverse delivered torque and prevent the apparatus from breaking down because of overload; it also simultaneously ensured the safety of the user.

As shown in Fig. 4, we used a preliminary design of the circular plate of \( \varphi 14 \) [mm] to perform the torque limit experiments in the beginning (Tanaka et al., 2017). In this study, we subsequently enlarged the circular plate diameter to
We designed the grooves on the inner surface of the final gear to confirm the torque performance. We employed various materials to investigate the limit torque and durability of the two kinds of groove designs. For this torque limiter, we developed an assistive walking device that not only maintained the device service life but also assisted the wearer to easily complete the dorsiflexion and plantarflexion motions. Thus, the delivered torque of the assistive device played a major role in the two motions. Using the two kinds of designs of the final gear in conjunction with different materials, we performed three experiments conducted by 1) limiting the torque, 2) limiting the torque by increasing the thickness of shim rings, and 3) S-N experiments. These experiments provided evidence of the maximum load torque and the durability of the rubber materials used in the different gears.

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\phi = 18 \text{[mm]} \quad \text{and} \quad \text{modified the surface shape design, as shown in the second graph of Fig. 4. We designed the grooves on the inner surface of the final gear to confirm the torque performance. We employed various materials to investigate the limit torque and durability of the two kinds of groove designs. For this torque limiter, we developed an assistive walking device that not only maintained the device service life but also assisted the wearer to easily complete the dorsiflexion and plantarflexion motions. Thus, the delivered torque of the assistive device played a major role in the two motions. Using the two kinds of designs of the final gear in conjunction with different materials, we performed three experiments conducted by 1) limiting the torque, 2) limiting the torque by increasing the thickness of shim rings, and 3) S-N experiments. These experiments provided evidence of the maximum load torque and the durability of the rubber materials used in the different gears.}
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3.2 Delivered Frictional Torque
3.2.1 Theoretical Formulation

In this study, we developed a torque limiter for a walking assistance device using the frictional torque delivered by the circular plate; this torque was generated because of the friction between the contacting surfaces. The delivered frictional torque plays a primary role in walking assistance devices. In this study, we assumed that uniform pressure was applied over the area of the circular contact surface. This torque calculation is shown in Fig. 5. Thus, the normal force (N) can be calculated as follows (Budynas et al., 2010):

\[
N = P_a \times \frac{\pi}{4} (D^2 - d^2),
\]

where the \(N\), \(P_a\), \(D\), and \(d\) are the normal force, the normal pressure, the external diameter, and the internal diameter, respectively. Then, the delivered frictional torque generated by the without grooves type (\(T_{w/o}\)) would include the torque generated by the normal pressure and the pressure of the lateral side; therefore, \(T_{w/o}\) can be expressed as follows:

\[
T_{w/o} = \mu \times P_a \int_{D/2}^{d/2} 2\pi \times r dr + \mu \times P_s \times A_{side} \times \frac{D}{2} = \frac{\mu N}{3} \times \frac{D^3 - d^3}{D^2 - d^2} + \frac{2\mu ND^2 w}{D^2 - d^2},
\]

where \(\mu\), \(r\), \(P_a\), \(A_{side}\), and \(w\) are the friction coefficient, an element of the radius, the pressure of the lateral side, the area of the lateral side, and the thickness of the material, respectively. The delivered torque given in Eq. (2) is for a single pair of mating surfaces. Furthermore, the delivered frictional torque of the with grooves type (\(T_w\)) can be expressed as follows:

\[
T_w = T_{w/o} + n \times F_s \times r_m = \frac{\mu N}{3} \times \frac{D^3 - d^3}{D^2 - d^2} + \frac{2\mu ND^2 w}{D^2 - d^2} + n \times \frac{\mu N}{A} \times A_g \times r_m,
\]

where \(n\), \(F_s\), \(A\), \(A_g\), and \(r_m\) are the number of grooves, the local shear force of the groove, the circular contact surface area, the projected area of the groove, and the equivalent radius. In Eq. (3), the term \(n \times F_s \times r_m\) refers to the additional torque caused by the local shear force from the squeezed material. In this study, there were six grooves (i.e., \(n = 6\))—the circular plate and the inner surface of final gear had three grooves each.
4.1.1 Experiment Using With and Without Grooves type

In this study, it was necessary to be cautious while selecting the material for the hollow rubber circular plate because the endurance and delivered torque capacity were important factors for maintaining the service life of this device. Hence, we conducted an experiment to confirm the limit torque of this mechanism for the various kinds of rubbers. In our previous research (Tanaka et al., 2017), we compared the plates of different diameters (φ14 and φ18 [mm]) with eight rubbers that did not have grooves. To confirm the performance of this torque limiter mechanism, we improved the surface shape design (for with and without grooves type) of the final gear. In this experiment, we used a plate having a diameter of 18 mm for each of the with and without Grooves type. Furthermore, we used five materials to assess the limit torque.
of this torque limiter. Figure 6(a) shows the schematic of the experimental setup used to measure the torque. The torque limiter experiment was set up as follows: 1) The servo motor was set up at a specified angle by the program. 2) An aluminum frame was used to emulate the cantilever beam and acquire the torque by changing the weight and the length of the frame. Additionally, we prepared five materials for the experiment: NBR (nitril-butadiene rubber), CR (polychloroprene, normal and soft type), TPO (thermo polyolefin), PVC (polyvinylchloride), Silicone rubber, Polyurethane rubber, and Polymer of styrene as shown in Fig. 6 (b).

![Schematic of torque measurement experimental setup](image)

(a) Schematic of torque measurement experimental setup

![Five materials used](image)

(b) Five materials used.

4.1.2 Torque Limit Experiment by Increasing Shim Ring Thickness

One of the important factors in the torque limiter mechanism is the normal force, which has a vital influence on the delivered torque. In this study, we attempted to increase the number of shim rings on the final gear, as shown in Fig. 3. By increasing the number of shim rings, the rubber circular plate of the final gear was forced to shift, and it was then subjected to the normal force. This experiment employed PVC and NBR to examine the load torque variation by increasing the number of shim rings for the gear without grooves type. The number of shim rings ranged from zero to five, and their thicknesses ranged from 0 to 0.5 mm.

4.2 Durability Experiment

To maintain the service life of this assistive device, we performed a durability experiment to examine the life of the rubber materials used in the with and without grooves type. The schematic of the durability test is shown in Fig. 7. In the durability test, the rubber material was subjected to cyclic load torques until failure (until the frame started going down). In the experimental conditions, we assumed that the person had overloaded twice in 1 min during continuous walking; this happens in real life when a person loses balance such as when stumbling or slipping. The experimental steps for a complete cycle are as follows: 1) Set the time interval to 30 s for unloading the torque state, and 2) After 30 [s], subject the rubber shim to the load for 5 [s]. Furthermore, the load torque of the durability experiment starts by delivering the torque required to complete the cycle loads until the rubber cannot maintain the load and failure. The load torque is then gradually decreased and the same experiment is carried out until the endurance limit of the rubber is attained. Therefore, the S–N curve can then be obtained.
5. Results and Discussion
5.1 Torque Measurement of Devices With and Without Grooves

From the results of the torque measurements for φ14 [mm] (Tanaka et al., 2017), it was clear that the NBR material had the highest delivered torque (2.9 [N·m]) as compared with the other four materials because of the high friction coefficient. However, the low friction coefficient of silicone rubber could hardly provide the transmitted torque. When we compared the small circular plate (φ14 mm) with the large circular plate (φ18 [mm]), we found that the NBR had elevated the delivered torque capability from 2.9 to 4 [N·m] (the rated output torque of the servo motor). Furthermore, when the rubber materials were placed in circular plates of diameters φ18 and φ14 [mm], the larger circular plate supplied a higher transmitted torque than the smaller circular plate. In the previous experiments, most of the materials cracked badly except for PVC and silicone rubber. Nevertheless, the torque limiter mechanism was considered for the assistive device so that a long service life could be maintained for at least over one year. The results indicated that the transmitted torque of the PVC plate was two-thirds that of the NBR plate. The results also showed that the three materials (CR (soft type), polyurethane rubber, and the polymer of styrene) were destroyed when subjected to the limit torque. Therefore, we removed these materials and chose the remaining types of rubbers; we used an φ18 [mm] circular plate to perform subsequent torque limit experiments in this paper.

During the experiments, we found that the slipping phenomenon had two phases. In phase 1, when the torque was constant but the torque load was increased, the torque limiter mechanism started to slip, but the frame retained its position. In phase 2, when the torque was constant but the torque load exceeded the critical value, the frame started to slip. In the slipping state, the surface of the sandwich material supplied the maximum static friction force required to maintain the final position. Therefore, the frictional coefficient of this type of rubber material had a vital influence on this device. Figure 8 illustrates the results of the torque measurement for the with and without grooves type for five types of rubber materials. The findings demonstrate that the with grooves type had a higher torque capacity as compared with the without grooves type. Moreover, when comparing the five kinds of rubber materials, the NBR and CR materials were found to be better than the other materials. Although the CR material was able to provide good torque performance, it was not good for use in the assistive device because it was badly destroyed when subjected to sudden overload. As revealed in Fig. 8, the gear with grooves type along with the NBR material achieved a torque limit of 4.5 [N·m]; therefore, NBR was considered the ideal material for assistive devices. However, the with grooves type when used together with the shim made of PVC also had the features of a good limit torque (3.8 [N·m]), and it did not crack easily; therefore, PVC is also good material for use in a torque limiter.
5.2 Comparison of Torque Measurement with Calculated Results

The efficiency of the torque limiter (of diameter 18 mm) was verified by comparing the numerical calculation with the measured results. We made observations by increasing the thickness of the shim rings from 0 to 0.5 mm. Figure 9 shows a comparison of the calculated limit torque results with the measured limit torque results when the NBR material was used. For the without groove type, when the number of shim rings was increased, the measured limit torque increased from 2.3 to 4 [N·m] and the calculated limit torque increased from 1.82 to 4.47 [N·m]. The calculated limit torque of the with grooves type increased from 2.02 to 4.95 [N·m]. The results indicate that the theoretical calculation slightly underestimated the measured results when the thickness of shim rings were increased from 0 to 0.2 [mm]. The torque limiter was locked by artificial means, which could have induced an unstable locked force; therefore, the measured results were high. However, when the number of shim rings (with a thickness greater than 0.3 [mm]) was increased, the internal space of the motor was forced to enlarge the space; therefore, the motor might have caused a small deformation. Therefore, the measured results had a different linear tendency, and the theoretical calculation was slightly higher than the measured results. In general, the validation illustrates that the overall tendency is in good agreement with the torque measurement. By using our proposed torque equation, we found that the theoretical and measured results between the gears with grooves and the gears without grooves were almost the same. Therefore, the present theoretical torque equation is enough to predict the torque limit for the torque limiter.

Fig. 9 Comparison of the torque measurement with calculated torque results.
5.3 Results of S-N Curve

Based on the results obtained in Section 5.1, we designated NBR and PVC as the main test materials. This study used the S–N curve to assess the durability of the two rubber materials in the with and without grooves type. Figure 10 (a) illustrates S–N curves of NBR obtained by changing the two types of gear. The results of the S–N curves demonstrate that the two types of designs (with and without grooves type) exhibited different service life cycles. The blue line represents the torque for gears with grooves; it has a steep slope. However, the red line, which represents the torque for the without grooves type, shows a gentle slope. The two S–N curves have two intersection points at (75.5, 2.85) and (181.2, 2.5). These results show that when the NBR material was employed in the with grooves type, the subject’s load torque was between 2.5 to 2.85 [N·m], and the service life was shorter than the that of the without grooves type, which used the NBR material. However, when the load torque was greater than 2.85 [N·m] or less than 2.5 [N·m], the with grooves type showed better service life than the without grooves type. Nevertheless, the S–N curves of the without grooves type show a very gentle slope, which also means excellent service life for the without grooves type. For instance, when the load torque was 2.6 [N·m], the service life cycles of the with grooves type was less than 100 cycles; conversely, the without grooves type produced more than 100 cycles. When the NBR material was used in the with grooves type, the S–N diagram becomes horizontal at 2.5 [N·m]. The load torque at this point is called the endurance limit, and it occurred at 92 cycles. Using the PVC material, we carried out the same durability experiments to compare the differences in the service life cycles of the with and without grooves type. As shown in Fig. 10(b), the two S–N curves have two points of intersection at (64.76, 2.67) and (803.78, 2). Consequently, the results indicate that when the PVC material was used, the without grooves type had a better service life cycle than the with grooves type when the load torque applied was between 2.5 and 2.68 [N·m]. Nevertheless, when the load torque was greater than 2.68 [N·m] or less than 2.5 [N·m], the service life of the without grooves type was inferior to the service life of the with grooves type. Besides, when the PVC material was used in a with grooves type, the endurance limit occurred at 2 [N·m] and started at 117 cycles. However, the S–N diagram illustrates that it is difficult to obtain the endurance limits when using a without grooves type. Finally, a major finding is that the service life of the without grooves type is superior to the with grooves type only in the region of the intersection points of two S–N curves. In the rest of the regions, the durability of the with grooves type is better than that of the without grooves type regardless of the materials used. In case of an accident, any loss of balance would induce an unpredicted load. For instance, when there is any loss of balance, such as stumbling or slipping, the device can withstand the instantaneous load torque. The S–N curves indicate that the with grooves type can withstand low load torques (2.5 [N·m] for accident situations) over 300 times, and they can withstand high load torques (4 [N·m] for accident situation) approximately 24 times. The results reveal that the with grooves type can transmit a high torque; however, the without grooves type is better for long service life.

![S-N curves of NBR material](image)
5.4 Comparison of Torque Limiter With and Without Grooves

The applicability of the torque limiter mechanism was confirmed by comparing the with grooves type with the without grooves type. Additionally, we examined the NBR and PVC materials for determining the delivered torque and the durability. As indicated above, the torque performance of the plate of φ18 [mm] was superior to that of φ14 [mm]. NBR and PVC were chosen as the primary assessment materials because they did not crack easily. Furthermore, we found that both designs had a vital influence on the delivered torque and on the durability. The results show that the with grooves type had excellent transmit torque performance appropriate for users requiring high assistive power, e.g., the elderly. Furthermore, the without grooves type had a long service life, which is required for healthy persons. On comparing the NBR material with the PVC material, the torque limit of NBR was found to be higher than that of PVC. The service life assessment shows that the NBR and PVC performances were roughly the same when the load torque applied was less than 2.5 [N-m]. In this study, we suggested the use of a plate of φ18 [mm] for two designs with and without grooves by employing NBR material for the torque limiter. This successfully prevented the assistive device from damage when used for assistive functions.

Finally, the developed torque limiter mechanism was assembled into the walking assistance device. Subjects confirmed that they could feel the difference when the device used the torque limiter. We tested the device by performing outdoor walking trial tests by allowing the subjects to wear the device and walk outdoors. The trial test included the following: 1) free walking (without wearing the apparatus), 2) walking while wearing the device without assembling the torque limiter into the walking assistance device, and 3) walking while wearing the device by assembling the torque limiter into the walking assistance device. The results showed that the ankle joint’s target angle variation data were not changed. The subjects stated that incorporating the torque limiter in the device helped improve the gait and made them feel comfortable. The targeted angle variation data were designed only for walking on level ground; therefore, the assistive device could adapt to various road conditions using the slipping function of the torque limiter mechanism. Based on the same concept, the control method of this assistive device was used for the angle variation control instead of the angle control. From the subjects’ feedback, it was clear that they felt that the assistive power increased by using the new torque limiter mechanism having plates with φ18 mm and grooves combined with the NBR material.

6. Conclusions

This paper developed overload protection by using a torque limiter mechanism to prevent apparatus breakage and
ensure safety for the user. This torque limiter mechanism compared the two circular plate designs (with and without grooves) made from a variety of materials to examine the applicability of the torque limiter mechanism. To extend the service life of the torque limiter mechanism, we applied the S–N curve experiment to evaluate the durability of the NBR and PVC materials in the gear designs with and without grooves type. The results showed that the plate of φ18 mm with grooves type using NBR material provided a high load torque that reached the rated torque of the servo motor. Therefore, the with grooves type is good for use by the elderly who need high assistive power because they lack the required muscle strength. By using the NBR material in the without grooves type, excellent service life was achieved; therefore, we recommend the use of the assistive without grooves type for patients requiring long-term rehabilitation. While walking, users frequently encountered sudden loss of balance such as stumbling or slipping. The results show that the torque limiter proposed in this study can respond well to the unpredicted load torque over 300 times for accidents. We incorporated this torque limiter into the walking assistance device, which was designed to be lightweight, small, and low cost. This apparatus can be used to promote exercise and neuro-rehabilitation by supporting only the ankle joint. By integrating the two torque limiter designs into the walking assistance devices, we could meet the different rehabilitation requirements of the user and prevent the breakage of the assistive device because of overload; they also offer the same assistive functions as the original design. In the future, to improve the torque limiter mechanism, we will consider the various groove designs in conjunction with new materials to determine the preferable durability and the maximum allowable torque. In addition, we will perform further investigations to assess the delivered frictional torque for the device with grooves.

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