Microcontroller controlled electromagnetic locking mechanism for a gear-based knee joint prosthesis

BIOMEDICAL ENGINEERING | RESEARCH ARTICLE

An investigation into a locking mechanism designed for a gear-based knee joint prosthesis

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Abstract: Background: The knee-locking mechanism in an above-knee prosthesis is crucially important to protect the prosthesis user from sudden falling down due to unexpected disturbance while standing upright. Method: An electromagnet-based knee-locking mechanism has been designed and developed for a gear-based knee joint prosthesis prototype. The electromagnet has been controlled by a microcontroller to lock and unlock the knee joint with the help of position data detection using a gyro sensor during the thigh movement. The functionality of the locking mechanism and the overall performance of the gear-based knee joint prosthesis have been tested through experiment. Results: The proposed locking mechanism incorporated in the modified gear-based knee joint is found working well with the program coded and loaded into the microcontroller. The prosthesis prototype is observed capable of recreating the lower-limb gait cycle closer to that of a healthy individual with the developed electromagnet based locking mechanism. Conclusions: Though measuring the stability performance was not possible due to the unavailability of proper testing facility, the knee-locking mechanism has been found ensuring the safety measure of that gear-based knee joint prosthesis to some reliable extent.

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PUBLIC INTEREST STATEMENT
A locking system has been developed for an artificial knee joint of a prosthesis (artificial leg) to ensure safety and to safeguard the prosthesis user from sudden falling down caused by any unexpected disturbance coming from unpremeditated sources, e.g., collision. An electromagnet- and microcontroller-based automatic knee-locking system has been designed to provide an effortless safety without any use of manual handling. The proposed knee-locking mechanism successfully eliminated the limitation of the gear-based transfemoral prosthesis (above-knee artificial leg), which was developed earlier. The modified gear-based prosthesis comprised of the proposed knee-locking mechanism was found functioning smoothly, and it was still found cheap and affordable to the low-income group of amputees (population who are missing leg).
1. Introduction
The passive type prostheses are being used extensively due to its cheap availability. Though the active type prostheses like microcomputer-controlled prosthetic knee joint (Aeyels et al., 1992), real-time controller-based hybrid ankle joint (Yu et al., 2016), quasi-passive ankle-foot prosthesis (Shepherd & Rouse, 2017), powered ankle prosthesis (Gao, Liu & Liao 2018), etc., are found very much promising in terms of functionality, the high price of the active type prosthesis is limiting its wide-acceptance among the low-income groups of people who are larger in proportion. The passive type prosthesis was introduced just to replace missing extremity. Despite initially, there was no control system incorporated, later some mechanical control system operated with cable (Millstein et al., 1986), cam-profile (Realmuto et al., 2015), spring-damper (Masum et al., 2014), hinge joint and supination/pronation (Minnoye & Plettenburg, 2009) have been added to the passive type prosthesis. The most recent advancement in passive-type prosthesis is gear-based knee joint prosthesis development, which has been proposed and developed by one of the authors of this paper (Bhuiyan et al., 2017). Even though different approaches have been tried and various designs have been proposed, the main objective of the prosthesis construction is to develop a missing extremity as close as possible to the respective healthy body parts in terms of structure and functionality.

A good functional prosthesis should have reliable stability during the support phase and controllable flexion and extension movement during the swing phase in order to approach the human normal swing of the lower limbs, and maintains body balance and natural gait (Xie et al., 2010). Prosthetic knee joint plays an important role in transfemoral lower-limb prosthesis in recreating flexion at the swing phase by transmitting the thigh movements to the shank and proving stability at the stance phase of the gait cycle. A good artificial knee should mimic the behavior of a biological knee by providing natural kinematics, high strength and stiffness required in the stance phase (Poliakov et al., 2016). In a prosthetic leg, the design of the knee joint is the most critical. During the stance phase of gait, a stabilizing torque at the prosthetic knee axis is required to keep the user upright and to prevent from falling down. The torque is typically applied via dampers, locks or brakes (Andrysek et al., 2019). Without this locking mechanism, the risk of falling down or buckling when accidentally hit by something or someone is higher. Though the gear-based prosthetic knee joint that reported in the previous work of the author(s) was found very promising in reproducing desired gait cycle movements and transmitting power from residual limb/thigh to prosthetic shank/pylon followed by prosthetic foot, the lack of proper locking mechanism in the prosthetic knee joint has made the users vulnerable to sudden falling down/unwanted falling down caused by the disturbance or unintentional collision or accidental hit by the passersby while standing upright (Bhuiyan et al., 2017). That gear-based knee joint does not have an appropriate stance-phase control or locking mechanism to support the user during the stance phase to prevent unwanted jerking and sudden falling down. Since a good artificial knee joint should be able to support users during the stance phase and provide flexibility during the swing phase, thus a locking mechanism has been proposed to improve the performance of the gear-based prosthetic knee joint. An electromagnet-based automatic locking mechanism has been designed and developed to overcome that limitation of the prosthetic knee joint and thus to secure stance-phase knee stability, reduce fall risk and ensure safety of the user.

2. Modified gear-based prosthetic knee joint
To fit the proposed locking mechanism into the gear-based knee joint, some modification to the components of the existing design was needed. The guiding plate of the prosthesis arrangement
has been extended up to the pylon, and a new component named shank ring made of stainless steel (ferromagnetic material) was added to the pylon of the modified prosthetic knee joint arrangement. The electromagnet was screwed to the guiding plate, and the shank ring was mounted opposite to the electromagnet on the shank rod. The stainless steel has been chosen for the shank ring to ensure enough electromagnetic force ($emf$) development to lock the pylon/shank rod upright firmly. The total weight of the modified prosthesis with the electromagnet, battery and control system arrangement was 1.5 Kg, which is considerably light. As this prototype was smaller in size than a real prosthesis, it is expected that the weight of the prototype that scaled up to a real size would still remain within the standard weight limits of an above-knee prosthesis available in the market. The modified design of the gear-based knee joint with the locking electromagnet installed is shown in Figure 1.

3. Electromagnet-based knee-locking mechanism
An electromagnet based locking mechanism operated with a simple control system has been designed for the knee joint prosthesis. A gyro sensor has been used to detect the angular movement of the thigh/residual limb, produce and send the signal to the controller to lock and unlock the knee joint. It has produced no signal when the angle of rotation was zero; however, it has triggered a signal to unlock the knee joint as the thigh moved to a certain angle. The knee joint was locked as long as the user standing upright, and it became unlocked when the user intended to ambulate his/her leg. The locking mechanism has been controlled by a microcontroller incorporated in the design.

The effectiveness of the locking arrangement would be largely defined by the permeability of the ferrite material used in making shank ring, which is the characteristic of a material representing the establishment of an induced internal magnetic field by an external magnetic field. In this case, the external magnetic field would be produced by the electromagnet. Permeability of materials also used to indicate how easily the magnetic flux is build-up in a material. It is also known as the magnetic susceptibility of material (Okman, 2007; ToolBox, 2016). Permeability of material is defined as, $\mu = \mu_0\mu_r$, where $\mu_0$ is the permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ Henry/meter) and $\mu_r$ is the relative permeability of material ($\mu_r = 1$ for air or vacuum) (Regtien & Dertien, 2018). The permeability of the stainless steel used for making shank ring is reportedly higher than $1 \times 10^6$ H·m$^{-1}$, which is quite large for enough $emf$ development and thus to attract and hold the
The attraction force produced by the electromagnet can be calculated using the equation $F = \mu N^2 I^2 A^2 \mu_0 L^2$, where $\mu$ is permeability of electromagnet core material (Henry/meter), $\mu_0$ is permeability of free space (Henry/meter), $N$ is number of turns in the winding, $L$ is length of flux path (m), $I$ is current in the wire (A), and $A$ is cross-section area of core material ($m^2$), and $F$ is attraction force (N).

The locking and unlocking actions have been performed with the combined use of a microcontroller and the electromagnet. The block diagram of the control system designed for locking mechanism is shown in Figure 2.

The circuit diagram of the control system has been designed using circuito.io, which is shown in Figure 3. The design of the control circuit consists of an Arduino microcontroller with the function of operating a gyro sensor to control the electromagnet, which in turn generates the magnetic field to lock the knee joint. The connections between the components are also illustrated in Figure 3. In this control circuit design, a 12 V DC lithium-polymer battery is used to supply power to the electromagnet because the output current of the Arduino microcontroller board is not enough to drive the electromagnet. This battery has an energy density approaching 200 W.h/kg and enables the electromagnet to work under any reasonable load coming from the prosthesis user, although to a limited range of locomotion (Sup et al., 2009). Apart from this, it is also recognized for its higher safety and thinner dimension (Imanishi et al., 2001).
Once the circuit construction is done, the program has been coded and loaded into the microcontroller in order to control the locking mechanism.

4. Testing the knee-locking prototype
The Arduino R3 UNO microcontroller integrated with other elements of the control circuit using a breadboard has been connected to the laptop via USB. The experimental setup is shown in Figure 4.

Then, the experiment has been carried out by following the procedure shown in Figure 5.

Before start testing the prototype, the program code which also known as a sketch has been developed for controlling the locking mechanism. Arduino program has been written in the Arduino Integrated Development Environment (IDE). After that, the sketch has been loaded in the Arduino controller for execution. The algorithm of the program is shown in Figure 6.

The initial readings captured using the gyro sensor were recorded prior to start the data collection. The program code was run on Arduino software, and the readings of yaw (y), pitch (p) and roll (r) were generated to test the program. Then, the values of “p” and “r” are put into the program code to serve as the conditions/logics to turn on or off the electromagnet. Though there was a sinusoidal fluctuation in “y” value readings during normal gait cycle; however, no significant change has been observed in the “y” values at the event of sudden disturbance in the form of collision. Therefore, only the “p” and “r” values have been used as logics/conditions in the program to control the locking mechanism. The similar observation has been reported by Beil & Asfour (2019).

For testing the functionality of the locking system, sudden forces have been applied at the upper end of the thigh rod by pulling it with a strap connected to a handy weight-scale while the shank rod lower end tip was restrained from sliding using some wedge.
Some 19.7 kg equivalent to 193.2 N sudden forces have been applied to the prototype to test the effectiveness of the locking mechanism. The test force that simulating the accidental hitting incident was calculated considering a 69 kg individual walking at a normal speed of 1.4 m/s collides for 0.5 s with the prosthesis user standing upright. The sudden torque has been applied for 0.5 s to recreate the situation as close as possible to the real accidentally/unintentional hitting incident for which the locking mechanism was developed. The collision force has been calculated using the equation $F = \frac{mv_f - mv_i}{\Delta t}$, where $m = 69$ Kg, $v_f = 1.4$ m/s, and $v_i = 0$ m/s and $\Delta t = 0.5$ s. The electromagnet used for this locking system was capable of producing/withstanding up to 200 N, which should be enough to provide adequate holding force for the locking mechanism in the event of unintentional hitting occurrence.

The program has been run while the thigh rod was rotated manually to test the performance of the locking mechanism. The controller has received input data from the gyro sensor, and the statuses of the corresponding locking mechanism are shown in the serial monitor of Arduino software.

The raw data from the serial monitor while ambulating the knee joint prototype have been saved in txt. file and then exported to Microsoft Excel for post-processing. The performance of the locking mechanism has been evaluated by calculating the standard deviation of the data collected when the output is on and off, i.e. locked and unlocked. Standard deviation is one of the measures of
performance. It is a measure by how much the values in the data set are likely to differ from the mean. Here the mean value is the initial condition value set to lock and unlock the knee joint. The calculated standard deviation data would tell how much the output differs from the values set in the program input. Besides this, three sets of knee joint angular position data have been obtained and plotted in a graph against the time interval to produce the gait cycle for the prosthetic knee joint. Then, these graphs have been compared with the normal human lower-limb gait cycle.

5. Performance of locking mechanism
The performance of the knee-locking mechanism has been evaluated from the perspective of functionality, and the performance of the prosthesis prototype equipped with the knee-locking mechanism has been tested from the gait cycle reproducibility aspect. As the prototype was smaller in size than a real prosthesis, it was not possible to test with the human subject. However, the prototype has been tested with external force applied. For gait performance analysis, steady forces have been applied manually at the upper end of the thigh rod with hand while the shank rod was free to move according to the thigh rod rotation.

The data recorded from the microcontroller during normal gait cycle movement are presented in Figure 7.

The graphical representation of the hundreds of thousands of data points has shown some regular sinusoidal fluctuation, which indicated toward smooth the gait cycle movements during ambulation.

The y, p and r values were again recorded under disturbance to access the performance of the knee-locking mechanism at the event of experiencing some unexpected sudden collision. These data are shown in the following Figure 8:

The position of the knee joint prosthesis and the corresponding status of the knee-locking mechanism recorded from the controller are shown in the following Figure 9.

Figure 9(a) shows the locked state of the prosthetic knee joint prototype when a sudden pulling force has been applied to test the stability of the locking mechanism. Figure 9(b) illustrates the
transition of the prosthesis from locked state to unlocked state whereas Figure 9(c) shows the sample data recorded from the control system corresponding to the changes.

From Figure 7, it has been observed that the locking mechanism has been functioning properly without any disturbance while reproduced the normal gait cycle movement in the lower-limb prosthesis. Even though y, p and r values fluctuated in a regular cycle during normal gait cycle movement, the contribution of the y-value fluctuation during the normal gait cycle movement was the highest, which is followed by the fluctuation of the p value and r values. The highest fluctuation of the y value can be attributed to the flexion and extension angles of the knee joint while ambulating at normal gait cycle speed. However, different nature has been noticed in the fluctuation of the data presented in Figure 8. The y-value fluctuation was found negligible, whereas the
p-value fluctuation during disturbance contributed the most and then the variation of $r$ value. The significantly low fluctuation of $y$ value was due to the no angular movement (ambulation) at the knee joint prosthesis while standing upright.

The data obtained from the experiment show that the locking mechanism working well with the developed control system. The locking mechanism triggers from one state to another state when both the “$p$” and “$r$” values are below the set limits/reference point, and trigger back when those values go beyond the set values, which are coded as logic in the program for the control system. The locked and unlocked states of the electromagnet-based knee-locking system are shown in Figure 10.

Though the data have been collected and logged throughout the cycle, only those data identified representing the transition of the locking mechanism from unlocked to locked, or locked to unlocked are presented in Figure 11. The raw data have been recorded for a period of over 25 complete cycles, which are then used to plot the graphs of Figure 11 to evaluate the performance of the locking mechanism.

The graph shows that the electromagnet was turned off when the conditions $p > -3^0$ and $r > 59^0$ were met, and turned on when those conditions were not met. In other words, the knee-locking mechanism remained inactive as long as $p > -3^0$ and $r > 59^0$ and became active when $p < -3^0$ and $r < 59^0$. From the experimental data, it has been found that the average standard deviation of the “$p$” values was 0.0577 for triggering the locking mechanism from locked to unlocked state and 0.3281 for triggering from unlocked to locked state. The average standard deviation of the “$r$” values was 1.0153 for triggering the locking mechanism from locked to unlocked state and 0.6650 for unlocked to locked state. The small values of the standard deviation indicate a very successful execution of the program. Therefore, it can be deduced that the locking mechanism has been functioned effectively according to the set program. Besides, it has been observed that the microcontroller was capable of giving very quick feedback in every interval of 0.054 s. Based on the
observation, it can be stated that the locking mechanism was very much responsive to the changes of “p” and “r” values in order to turn on or off the electromagnet.

From the material aspect, the stainless steel used in making the shank ring was found performing well in the locking mechanism. The electromagnet used could generate holding force up to 20 kg to attract the shank ring during the stance phase and release during the swing phase. The test showed that the emf generated by the electromagnet was good enough to attract the shank ring and hold it firmly to its position while on, thus to lock the prosthetic knee joint and provide stability/safety to the prosthesis user (ref. Figure 19(a)). Therefore, it can be claimed that the locking mechanism incorporated in the gear-based knee joint was capable of supporting the users to some adequate level when standing upright.

The functionality of the locking mechanism has been tested from the gait cycle aspect also. The data of the knee joint angular position at the different points of time during the test were captured and recorded to correlate with the locking system data. The raw data with a sampling frequency of 100 Hz have been chosen from three sets of data obtained from the experiment to use for calculating the knee joint angles. The data have been used to plot the gait cycle graph of the knee joint against the time interval. The graphs are shown in Figure 12.
The pattern of changing the angular position of the prosthetic knee joint in Figure 12(a) is quite similar to the shape of a healthy human knee joint gait cycle during normal speed walking of Figure 12(b). The design of the gear-based knee joint prosthesis equipped with the locking mechanism has maintained a similar trend throughout the swing phase, though the magnitude of the knee joint angles was not exactly the same. This can be attributed to the fact that the experiment has been carried out by rotating the thigh rod manually. This is similar to the real-life situation, where the knee joint angular position varies based on walking speed, stepping length, etc. From Figure 12(a), some phase differences between the graphs have been observed, which indicated the different speeds used for rotating the thigh rod during the experiment.

Therefore, it can be concluded that the proposed locking mechanism in the gear-based knee joint does not affect the movement of the knee joint, and helps the gear-based knee joint prosthesis to reproduce the movement of a healthy biological knee joint effectively. In addition, the proposed locking mechanism was found capable of providing enough stability during the support phase when it is at the locked state. Hence, it can be stated that the integration of the knee-locking mechanism into the gear-based knee joint would improve the performance of the lower-limb prosthesis in terms of functionality. As the proposed electromagnet-based knee-locking mechanism is automatic, functionality wise it is better than SPS-3R41 knee lock (Author, 0000), which is operated manually using a pull cable. It is also found capable of ensuring more safety than the simplified active stance-phase lock (SASPL) (Andrysek et al., 2011). This is because, the SASPL is designed only to ensure smooth gait cycle movement, whereas the knee-locking mechanism presented in this paper is observed capable of safeguarding prosthesis user from unexpected fallen down due to unintentional disturbance while standing beside ensuring the smooth gait movement.

On the other hand, the primary focus of the proposed gear-based knee joint design was to develop some low-cost prosthesis. The inclusion of the cheap microcontroller and electromagnet based locking mechanism would increase its price slightly about 28 USD.50; however, it would still remain within the affordable range to the targeted low-income group of people.

6. Conclusions
The locking mechanism designed and developed for the gear-based knee joint prosthesis has been found functioning very effectively, and capable of locking and unlocking the knee joint as per the program coded and loaded into the microcontroller with a minimal response time of 0.054 s. The gait and motion study results have shown that the locking mechanism worked properly without affecting the gait cycle movement of the prosthetic knee joint. In addition, the electromagnet-based locking mechanism facilitated the gear-based knee joint in recreating the lower-limb gait cycle closer to that of a healthy individual. Though it was not possible to measure the stability index due to the unavailability of testing facility, it has been observed that the knee-locking mechanism would enhance the stability performance and safety measure of that gear-based knee joint prosthesis to some satisfactory level.

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