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学位論文題目	A Pedaling-Assistive Control Method of a Cycling-Wheelchair (足こぎ車いすのペダリング支援制御手法)
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## 論 文 内 容 要 旨

In developed modern caring technology, individuals with lower-limb disabilities can access a range of devices appropriate to their level of mobility such as canes, wheelchairs, and walkers, or even fully electrified mobility such as electric wheelchairs. Wheelchairs are the most widely used, because they are applicable to wide range of disabilities. Also they are quite inexpensive to afford. However, permanent wheelchair occupancy poses risks to the heart and upper limbs and interferes with blood circulation. Eventually, patients may become afflicted with “disuse syndrome,” which weakens muscles and bones of lower limbs for not being used in a long time. Even if the lower limbs are disabled, they need certain activity to maintain their essential function. Rehabilitation is one way to maintain lower limbs and hopefully to recover its function, which has to cover also for daily loss of not using lower limbs. On the other hand, in daily use of wheelchair or other non-electrical kinds of equipment, over-use of healthy part causes another problem. Since lower-limbs are disabled, these kinds of equipment require covering the lower limbs function by other healthy part. However, it is also said that daily use of wheelchair causes some problems that over-use of upper limbs may hurt the joints.

The recently-introduced cycling wheelchair is an offshoot of functional electrical stimulation (FES) studies. In FES, human muscle movement is stimulated by functional electricity. FES has been utilized as a walking aid for paraplegic patients. The idea is based on ergometer rehabilitation, which pedaling motion trains disabled lower limbs, with the patient’s upper limbs settled on either bed edge or chair. User of the cycling-wheelchair pedals with both of his/her legs. Though it may sound awkward that lower limbs disabled patients to pedal with

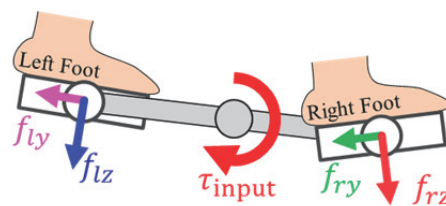


Cycling Wheelchair “Profhand”  
by TESS Co., Ltd.

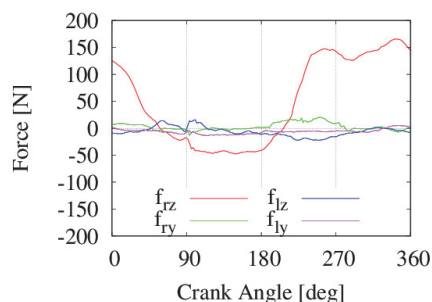
their disabled legs, it has proven to be possible. It was mainly used by lower limbs disabled patients such as paraplegic patients and hemiplegic patients. The device is primarily used in rehabilitation facilities and indoors. Recently as it is more popular and widespread, it is more often used in daily lives. The use of cycling wheelchairs in daily lives has started to point out some problems. While very easy to drive, even by patients with moderate to severe lower-limb disabilities, uphill travel presents a major challenge, while downhill travel is dangerous. Furthermore, uneven surfaces and narrow corners may be difficult to travel even by unimpaired users. A promising solution to these problems is power assistance.

In Chapter 2, investigation load on users in everyday environments is conducted by measuring tread force on pedals of the cycling wheelchair. Lower-limb disabled subjects and unimpaired subjects are participated. The environments include uphill, level difference, rough road and turns. Results show that hemiplegic subjects with only one unimpaired leg placed large load on their healthy limb. It intends to support the background that hemiplegic patients rely on their healthy side. Results also show that some of the users could not summon sufficient power for uphill travel. The tilt angle of uphill is set to 4%, which is still very loose inclination for daily environment, which implies strong necessity of power assistance.

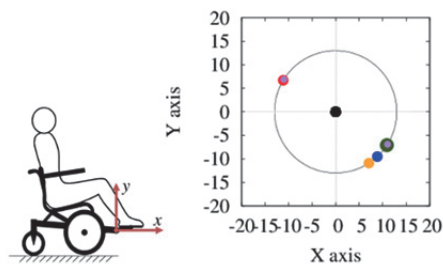
In Chapter 3, a new pedaling assistive control is proposed. As relying on healthy part when hemiplegic patients are riding the cycling wheelchairs is discovered in the investigation, over-use of healthy part in daily use of the cycling wheelchair is another problem. Still more, for patients who are not able to bend one leg because of the other side either is stiffened of the knee joint or physically not exists, the cycling wheelchair is hard to ride with one leg. For the second step, crank torque during one-leg-pedaling is discussed and a pedaling assistive control is proposed. Pedaling characteristics by considering one leg pedaling is discussed to verify the elements of pedaling. The pedaling torque is divided into 2 elements; torque exerted by human leg joint torques and torque exerted by gravity of the leg parts. As a result, the pedaling torque shows wavy form due to pedal position significantly, that is, difficulty and easiness of pedaling varies due to pedal position. From this characteristic of pedaling, a pedaling assistive control for one leg pedaling is constructed. The basic idea of the pedaling assistive control is to multiply human input by a function of pedal position,



Pedaling Torque and Tread Force

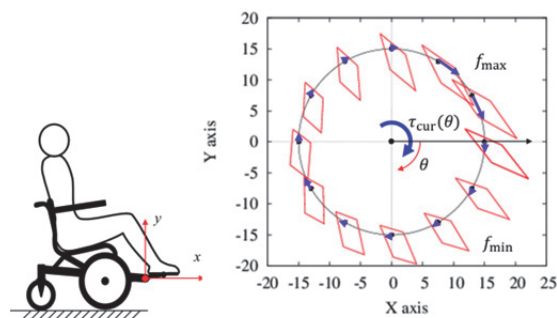


Tread Force of a Hemiplegic Subject on an Uphill Incline



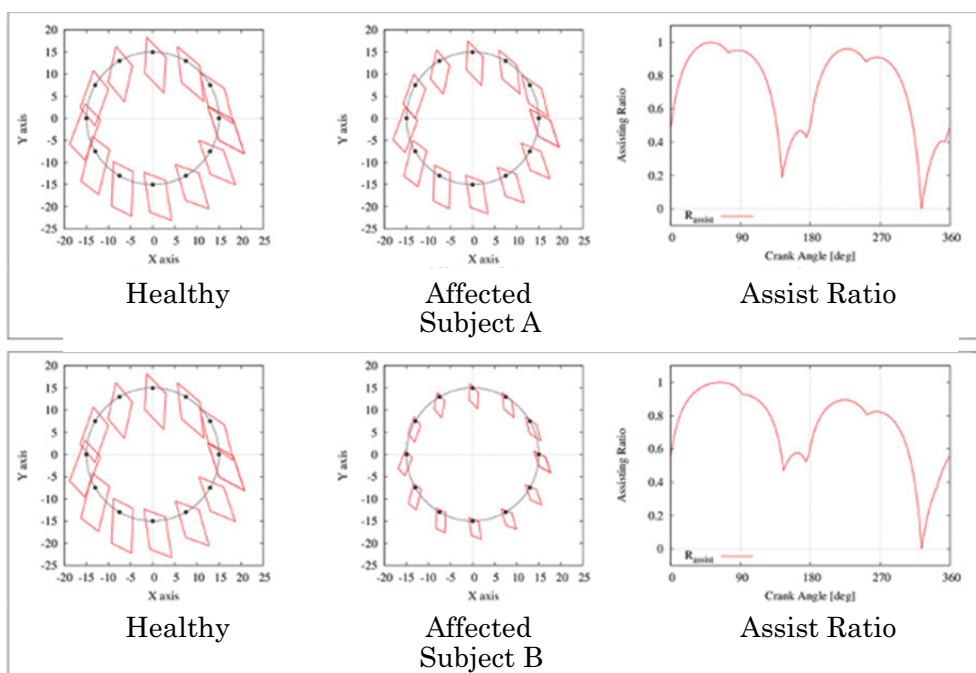
Positions of Healthy Feet where Pedaling is Difficult

so that it gives larger assist at where it is difficult to apply large torque and smaller assist at where it is easy to apply large torque. The function is determined by possible crank torque at each pedal position in pedaling cycle. The possible crank torque is obtained by capacity of human leg torque and gravity on human leg. The capacity of human leg torque was researched through. It is found out that human leg joints have tendency that flexor-extensor torque ratio is around 0.5. Considering all the above elements, function of assist ratio is determined. Also, inclusion of gravity on human leg in input torque has to be considered. In this control method, the gravity on human leg is removed to find the torque that the user attempts to pedal. Finally, the torque user attempts to pedal is multiplied by the defined function of assist ratio to realize the pedaling assistive control. Experimental result on plane by one leg shows significant improvement on user load.



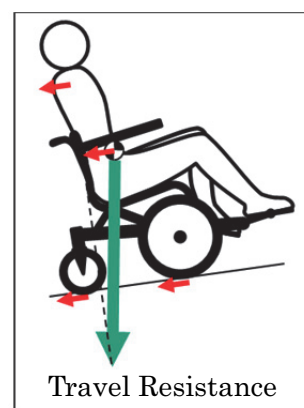
Potential Tread Force on the Pedal

In Chapter 4, the pedaling assistive control is expended for hemiplegic users. Hemiplegic patients have different joint torque capacities depending on their degree of symptoms. The affection is not always complete, for example the affected side can exert half the strength of the healthy side. When affected side is at the pedal position capable of exerting large force and the healthy side is not, assist is needed. In this kind of situation, the amount of the assist needed is different due to individual level of affection, for example when affected side is capable of half the strength of the healthy side, less assist is needed than when it is completely disabled. Thus the level of affection for individual patients should be considered in the pedaling assistive control typically for hemiplegia. The experimental results show validity of the proposing control by showing reduction of work required in a pedaling cycle.



Assist Ratios for Each Individual

In Chapter 5, environment adaptive power assist control is discussed. Power-assisting a mobile system is real-used typically on bicycles, or other is on wheelchairs. The previous power assistance control multiplies load of user by constant. This method is expanded for lower-limb disabled users in Chapter 3. However, it is not applicable for various environments. For example, it may not be enough for overcoming very steep uphill, it may be over assisting on plane, or it may be even dangerous on downhill. Power assisting control that changes automatically due to environment is needed. Power assistance control based on disturbance observer has been applied on bicycles and wheelchairs, for its flexibility that it controls the velocity of the system to imitate the given motion equation in any environments. It can be used on uphill, downhill and even other environments such that level differences. Thus, the traveling resistance compensation control is applied to the cycling wheelchair. Its effectiveness is evaluated on the same travel course as used in the previous investigation. In this test, the resistance is adjusted to match the capabilities of the user by altering the compensation ratio. In the latter part of the chapter, the traveling resistance compensation control is integrated to the pedaling assistive control, in order to realize adaptive control for various environments applicable to wide range of users including hemiplegic patients and one leg pedaling users. The control is tested by three subjects, showing its validity in required work per pedaling cycle.



# 論文審査結果の要旨

社会の高齢化とともに、下肢障害者数が増加しており、下肢障害者の日常生活支援を目的とした、各種移動支援システムが提案されている。足こぎ車いすは、歩行が困難な片麻痺患者でも利用できる移動支援システムとして近年注目を集めているが、施設内などの平坦な環境での移動を目的として開発されており、屋外での利用を前提としたシステムの開発が望まれている。本研究は、歩行が困難な片麻痺患者の利用を前提とした、足こぎ車いすのペダリング支援制御手法を提案するもので、全編6章からなる。

第1章は序論であり、本研究の背景、目的および構成について述べている。

第2章では、片麻痺患者(9名)と健常者(12名)を対象に、足こぎ車いすを利用する際のペダリングトルクを計測し、片麻痺患者と健常者のペダリングの違いについて考察している。そして、片麻痺患者の場合には、主に健脚でペダリングトルクを発生しており、ペダリングトルクに対する患脚の寄与が小さいため、ペダルのクランク角度によっては大きなペダリングトルクの発生が難しく、これが日常環境での足こぎ車いすの利用を困難にしていることを明らかにしている。これは、重要な知見である。

第3章では、片脚のみで足こぎ車いすの利用を可能にすることを目的として、足こぎ車いすのペダリングアシストシステムを提案している。本システムは、ペダリング支援トルクをアクチュエータで発生し、利用者のペダリングトルクに付加することによって、足こぎ車いすでの移動を支援するもので、利用者が発生できる最大ペダリングトルクとペダルのクランク角度との関係を解析し、それに基づき、ペダルのクランク角度に応じてアシスト率を変えることで、なめらかなペダリングが実現できることを示し、実験によって、その有効性を確認している。これは重要な成果である。

第4章では、より効果的な支援を目指して、前章の結果を両脚でのペダリングに拡張している。健脚と患脚それぞれの状態に応じて、発生可能な最大ペダリングトルクとペダルのクランク角度との関係を導出し、クランク角度に応じてペダリングトルクアシスト率を可変にすることで、なめらかなペダリングが実現できることを示し、実験を行いその有効性を示している。これは、有益な成果である。

第5章は、前章でのシステムに、坂道などでも平地と同様に走行することを可能にすることを目的として、走行抵抗補償制御システムを組み込み、片脚でも両脚でも、坂道を平地と同様に走行できることが可能になることを実験により示している。これは、本システム実用化のための重要な成果である。

第6章は結論である。

以上要するに本論文は、片麻痺患者など下肢障害者の利用を前提とした、足こぎ車いすのペダリング支援システムを提案するもので、バイオロボティクスおよび機械工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。