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A Technical Note

An international track wheelchair with a center of gravity directional controller

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Abstract—An international track wheelchair (ITWC) with a center of gravity directional controller (COGDC) is described in this paper. The rules for international track competition disallow devices designed solely for steering. Equipment has been disqualified for having steering handles, crown compensators, and other lever systems. However, the rules do allow tie-rod linkage and the use of springs for dampening caster flutter. The chair described in this paper exploits the physical properties of wheeled vehicles to achieve directional control on the track. This controller is effective, because turning is only required in one direction. Three such track wheelchairs have been developed and were used at the Paralympics in Seoul, Korea, in October of 1988.

Key words: *center of gravity directional controller (COGDC), international track wheelchair (ITWC), spinal cord injured athletes.*

INTRODUCTION

The 1988 International Stoke-Mandeville Games Federation (ISMGF) rules for athletics disallow the use of any device solely designed for the purpose of steering. In the past, wheelchairs have been disqualified for having steering levers, crown compensators, and other lever- or cable-operated devices. The lack of steering equipment has restricted the performance of those individuals with higher levels of paraplegia, and with quadriplegia (2). For those unable to use their hip and leg muscles, the force required to change direction in the turns must be generated by the right arm through the push-ring, causing premature fatigue of that arm and a higher incidence of injuries to the right shoulder (7). The National Wheelchair Athletic Association (the governing body for wheelchair sports in the United States), in reaction to these problems and issues of safety, changed its rules in 1982 to allow the use of steering devices. However, when U.S. athletes compete in international events, they are required to compete under ISMGF rules, and must adapt to an international track chair. In addition, foreign athletes have an advantage because they compete solely in international track chairs and with great success. This has prompted an interest in developing international track chairs that would allow U.S. athletes to be more competitive abroad.

The ITWC described in this paper is depicted in **Figures 1 and 2**. A unique feature of this ITWC is the front end (**Figures 3a and 3b**). This three-wheeled wheelchair uses a trailing arm to mount the front wheel and a newly-developed directional controller. Although trailing arms have become standard on four-wheeled racing wheelchairs, they have not previously been used on three-wheeled racing chairs. This is partially due to the problem of the directional instability that results from the use of a cantilever axle mount for the front wheel. One solution to this problem is the directional controller (stabilizer) used on the wheelchair described in this

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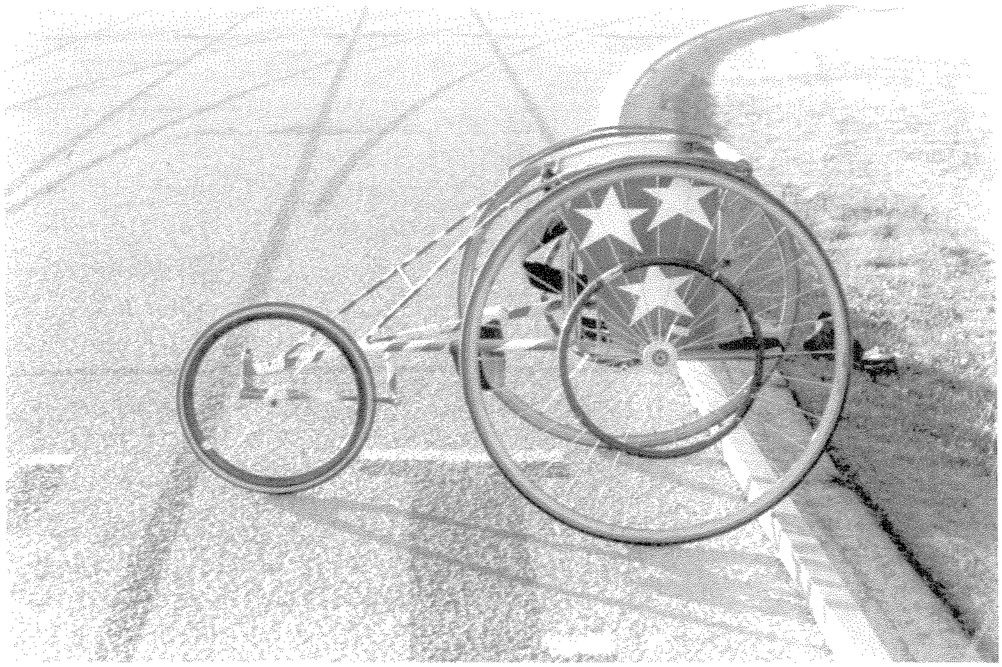

Figure 1.
The three-wheeled center of gravity international track chair.

Figure 2.
Front view of the track chair.

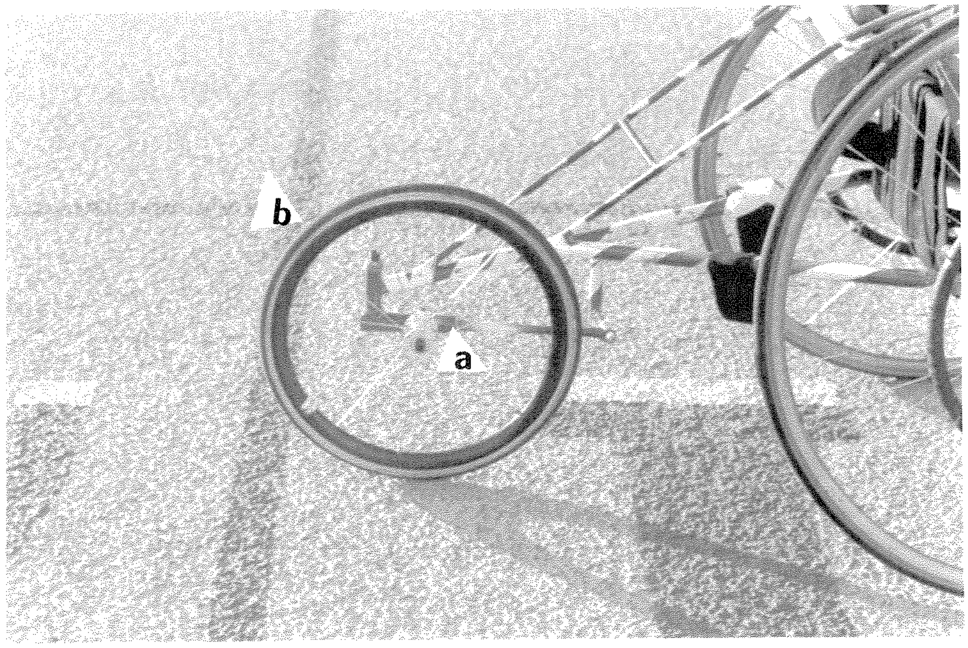

Figure 3a.
A close-up view of the front end exposing the relation of the front wheel to the trailing arm. Note that the hub of the front wheel is supported on only one end. a: Trailing Arm, b: Front Wheel.

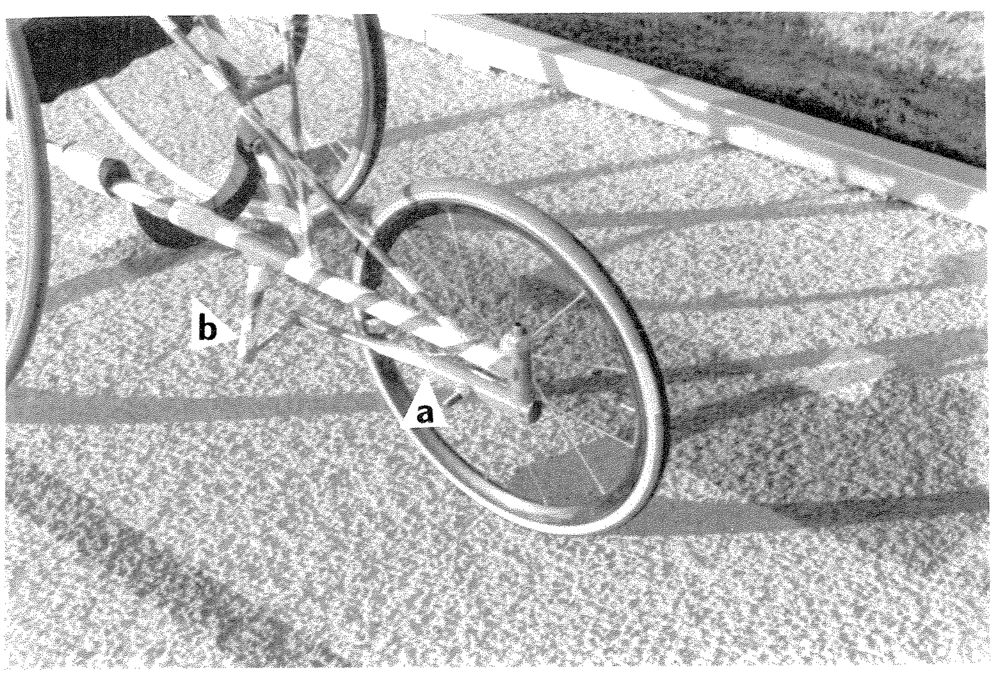

Figure 3b.
A close-up view of the front end depicting the trailing arm and directional controller (stabilizer). a: Trailing Arm, b: Directional Controller.

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paper. The directional controller serves a dual role in this instance: directional stabilization of the front wheel, and directional control through changes in the position of the center of gravity.

PROBLEM DEFINITION

The purpose of this investigation was to develop an ITWC that would be easier to propel through the turns than would a standard track wheelchair (without steering), and yet still satisfy the ISMGF rules for athletics. The final design was built and tested in actual competition at the 8th Paralympics held in Seoul, Korea in October, 1988.

METHODS

ITWCs are single-purpose pieces of equipment that do not require many of the features of road-racing wheelchairs, since the track used is a strictly-controlled arena. They are not allowed to contain steering devices or crown compensators, and do not, in general, require brakes. In addition, three-wheeled chairs are often used because of their light weight (which aids in acceleration, since surging is a common tactic employed in track racing), and also because of their ability to turn more easily than four-wheeled chairs. Track wheelchair frames can be built lighter because they do not require much of the bracing needed for road racing (i.e., there are no pot holes, downhills, or other surface irregularities in an arena).

The fact that track chairs are required to make only left-hand turns is of major importance. One might argue that right-hand turns may be required in order to overtake a competitor. The occasion to make a right turn seldom occurs, but it *can* be done by lifting the front wheel and placing it at the desired angle. Therefore, one focuses on a specific solution for making left-hand turns. The method employed in this design is described in the next section.

Static analysis

The purpose of this analysis was to develop a theoretical basis for the design of a COGDC. The variables used in this analysis are as follows:

b = coefficient of rolling resistance
f_r = rolling resistance of the front wheel
f_s = spring force
g = acceleration due to gravity
$l(x)$ = horizontal distance of center of mass to the rear axles
L = length of the trailing arm (from the center of the front housing [pivot point] to the directional controller [stabilizer])
M = mass of the individual and racing wheelchair
N_f = normal force of the front wheel
o_f = offset of the front wheel from the center of the front housing (pivot point)
r_f = radius of the front wheel
WB = wheelbase
x = position along the axis of the track.

The COGDC takes advantage of the fact that frictional forces act upon the rolling track wheelchair, and those forces are related to the normal forces of each of the wheels (in addition to other variables such as tire pressure, track hardness, tire diameter, and type). It was hypothesized that if the direction of the front wheel could be influenced by manipulating the position of the center of mass, some directional control could be achieved that would be considered legal under ISMGF rules.

The equation for rolling resistance is (1):

$$f_r = N_f b / r_f \quad [1]$$

The relationship between the normal force of the front wheel [N_f] and the position of the center of mass can be derived by taking the sum of the moments about the rear axles.

$$Mgl - N_f WB = 0 \quad [2]$$

After some manipulations:

$$f_r = Mgl(x)b / WBr_f \quad [3]$$

Equation [3] relates the position of the center of mass [$l(x)$] to the rolling resistance acting on the front wheel [f_r].

If a three-wheeled design is chosen, then this relationship can be exploited to assist with turning in one direction. If the front wheel is mounted to a trailing arm with a cantilever axle (an axle that extends from only one side of the hub; also known as a side-mount axle) (see **Figure 4**), there will be an

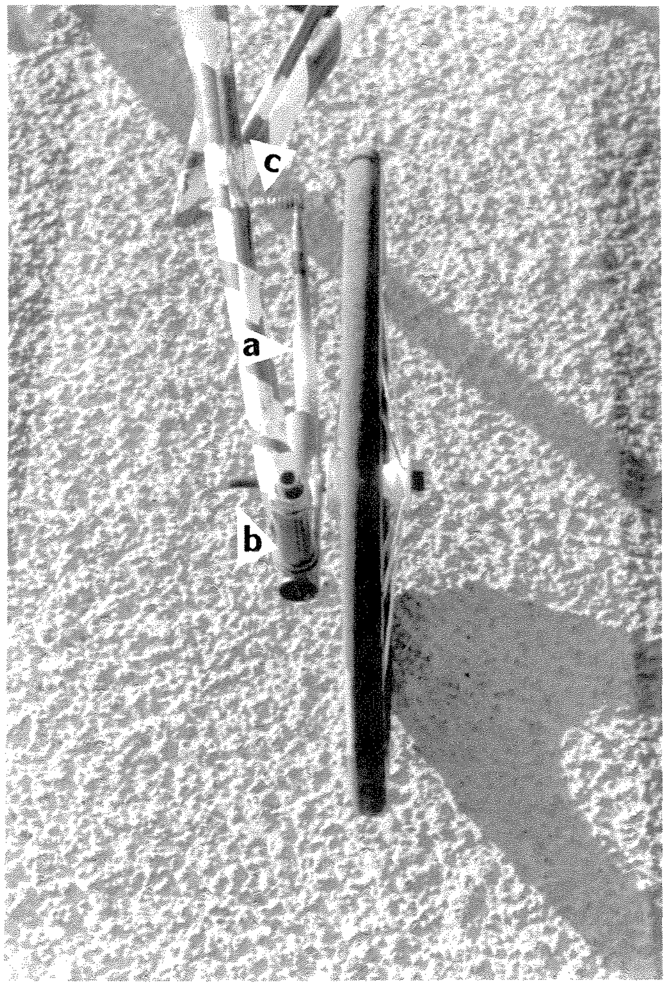

Figure 4.
Top view of the front wheel assembly including the directional controller (stabilizer). a: Trailing Arm with cantilever axle, b: Front Housing (Pivot Point), c: Directional Controller.

offset between the center of the front wheel and the front housing (pivot point). The rolling resistance of the front wheel acting upon the track surface will cause a moment to be generated about the front housing (pivot point). If the front wheel is mounted closer to the axis of the track, inside of the front housing, the track chair will have a tendency to roll to the left. This moment can be exploited to help steer the chair around a corner; however, some form of controller is required. Without a controller (stabilizer), the front wheel will turn until either the chair upsets or the components of the forces acting upon the front wheel are in equilibrium. In general, the propelling forces are rhythmic in nature, and the front wheel direction would oscillate. A simple spring can be used to generate a restoring force to achieve directional control. It is well known that spring force is proportional to the displacement (for small displacements), and therefore ideal for this type of controller or stabilizer. To illustrate this point, the moments about the front housing (pivot point) are analyzed.

The sum of the moments about the front housing (pivot point):

$$f_s L - f_r(l,x)o_f = 0 \quad [4]$$

Hence the direction of the front wheel is related to the spring force which can be controlled by the changes in position of the center of mass. The controller, which satisfies equation [4], that was

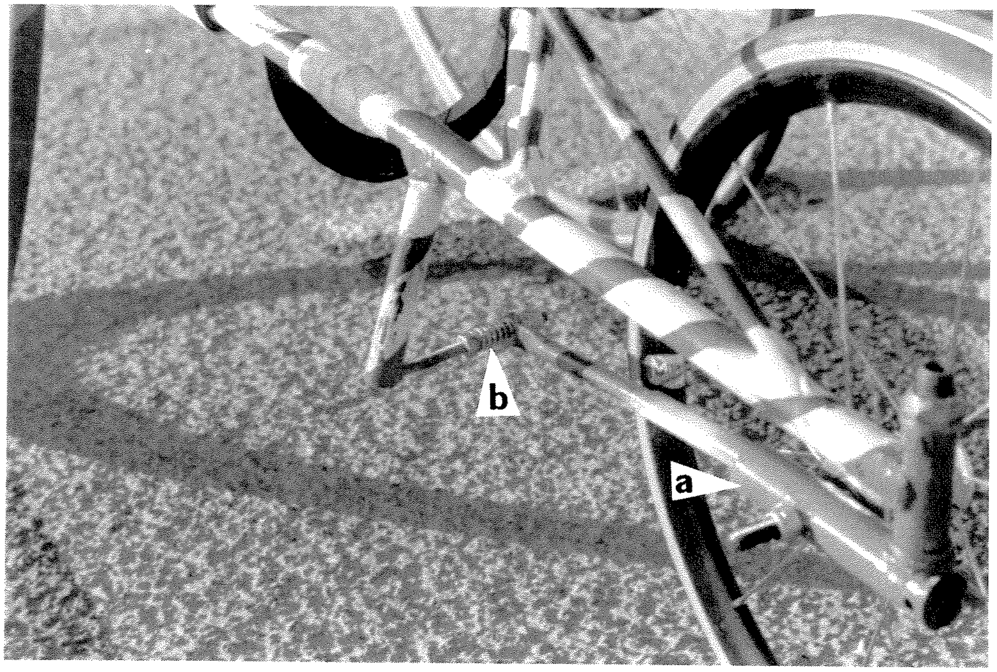

Figure 5.
A close-up view of the trailing arm and the directional controller (stabilizer). a: Trailing Arm, b: Directional Controller.

used on the ITWC herein described, is depicted in **Figures 5 and 6**.

The control variable for this system is the position of the center of mass. The limits of the control are individualistic and dependent upon the nature, extent, and level of disability of the user. The greater the range of controllable movement of the upper body, the greater the control of direction. In most cases, the upper legs can be used as a limiter. The individual can lie on his/her knees in the turns, moving the center of gravity forward; then sit more upright in the straight sections of the track, thus moving the center of gravity back to the former control position.

$$l(x) = \frac{l_{straight}}{l_{turn}} \quad [5]$$

The control input can be thought of as a switching function. The center of gravity in a track wheelchair actually oscillates about a nominal value (8) during propulsion, as greater force can be applied to the push rings by imparting some of the momentum of the trunk. Thus, for the switching control of equation [5], the position of the center of gravity for the straights [$l_{straight}$], and for the turns [l_{turn}], are the nominal values about which the center of gravity oscillates on the straights and turns, respectively.

Testing

The design was tested by constructing an ITWC and having spinal cord injured paraplegics train and race in the chair on a track for approximately 100 hours. The subjects performing the bulk of the testing were T9/10, T7, and T10 traumatic spinal cord injured track athletes. Each had a minimum of four years' experience in racing wheelchairs. The chair behaved as expected from the static analysis. The object of this paper is not only to describe the design, but to explain the logic behind the design as well. It is the desire of the author to present more in-depth analyses of the experimental parameters involved in the future.

RESULTS

Three chairs have been constructed and are in use by different people. It is the consensus of these users that the characteristics of each track wheelchair are highly individual. The basic principle and design are sound and have been adopted by three

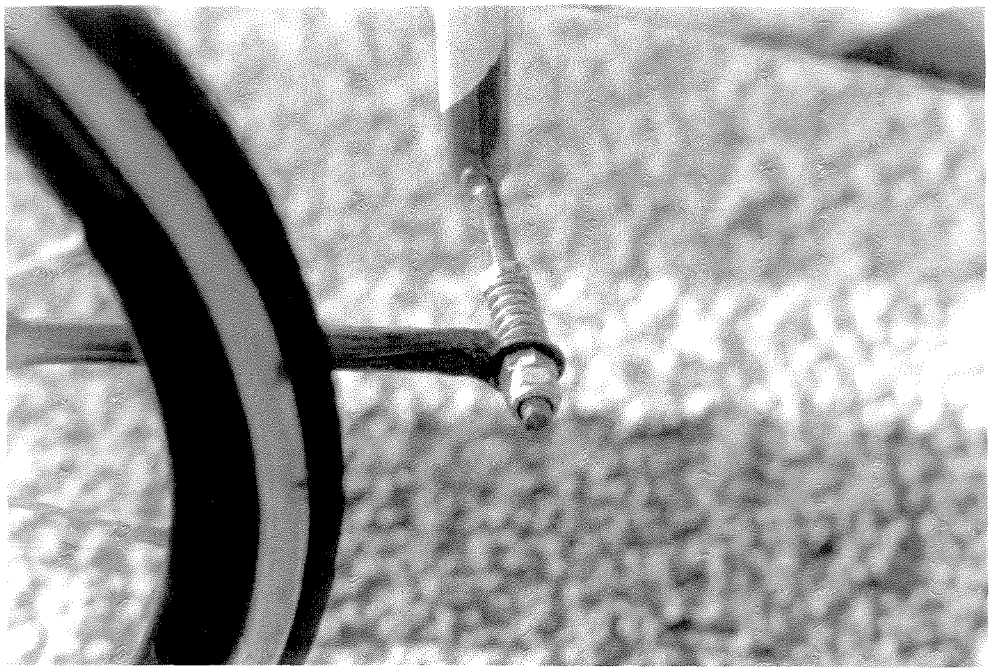

Figure 6.
A close-up view of the directional controller (stabilizer).

members of the United States Paralympic team. The chair has been added to the product line of Eagle Sports Chairs, Inc. The problem of presenting any quantitative results stems from the issue of range-of-motion and personal preference in the positioning and handling characteristics. It is not possible to draw any conclusions as to what the range of spring forces, size of the front wheel, or length of the trailing arm should be from such a small sample size, variations in track surfaces, and individual users. The people using the COGDC have explained that it is easier to control than other international track chairs they have used, and their success in qualifying for the United States Paralympic Team warrants some attention. The spring tension on the controller spring can be adjusted to suit both the individual's preference and the surface of the track during race conditions. In general, the tension on the controller spring and the position of the individual's center of mass must be found iteratively.

DISCUSSION

The objective of this investigation was achieved. An alternative method of controlling an ITWC was developed and three chairs have been built. The COGDC method needs to be studied further, so that its full merit can be established. Previous ITWCs have been variations on the center-of-gravity chair (3,4). The limitation of the center-of-gravity chair for this application is that, in order to achieve the directional instability required to maneuver the chair around a corner at racing speeds (8 m/s), the individual must sit nearly up-right in the turns so that he/she may lean forward on the straights to put greater power on the push-rings. Thus, the center of gravity of the individual and the chair is located near the rear axle in the turns, and forward of the rear axle on the straights, allowing the chair to be turned easily by differential pushing on the push-rings in the turns. However, little power can be applied for propulsion, as the chair would then have too great a tendency to "do a wheelie" (6). The COGDC herein described does not have that problem, because the center of gravity remains in front of the rear axles, thereby allowing the optimal force to be applied in both the turns and the straights (8,9). The COGDC allows the individual to push through the turns, whereas in a normal track wheelchair, speed is gained on the straights, and the rider attempts to maintain speed in the turns.

Another apparent advantage of this design is that the chair tends to feel stiffer than other track chairs used by our subjects. This is probably due to the shorter moment arm between the frame and the track. This design uses a trailing arm which brings the frame down to axle height; typically, forks have been used with the frame attached above the wheel.

SUMMARY

We have described a new method for performing turns in an international track wheelchair. Although the results are preliminary, it appears that the COGDC shows promise. Further investigation is required to determine the optimum position of the center of gravity for propulsion and for steering. That will be the topic of a future paper. A larger sample size will be required to determine the biomechanically optimal position for wheelchair propulsion. This paper presents only one possible controller; other methods need to be investigated as well.

Investigations of wheelchair sports performance are only preliminary (5), and there are a number of problems to be investigated: the effect of push-ring shape on propulsion efficiency; the effect of various contact surfaces; the investigation of various stroke kinematics and biomechanics; alternative arm-propelled vehicles; and, the design of improved wheelchairs. The spin-off of improvements in sport technology to everyday use has already been documented.

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