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A steering linkage for short wheelbase vehicles: Design and evaluation in a wheelchair power base—A technical note

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Abstract—An Ackerman steering linkage for short wheelbase, four-wheel vehicles has been developed. The linkage coordinates the steering angle of each wheel through a range of 180° with minimal misalignment between wheels. Control of steering angles is accomplished using a single linear actuator. Control complexity is lower compared to four-wheel systems using individually controlled steering actuators for each wheel. A prototype linkage that provides a minimum turning radius while maintaining maximum stability has been developed and evaluated for a power wheelchair base. The single-actuator linkage is well suited for this application, due to the cost-sensitive nature of wheelchair products.

Key words: *spinal cord injury, steering linkage, wheelchair.*

INTRODUCTION

Characteristics of Wheelchair Drive Configurations

The ability of the user to maneuver a powered wheelchair in confined spaces is closely related to the wheelchair's drive and steering configurations. The most common drive configuration, differential rear-wheel drive, consists of fixed and driven rear wheels with front caster wheels (1). Direction changes are made by individually varying the speeds of the rear wheels. In this configuration, the point about which the wheelchair pivots lies on a line perpendicular to, and running through, the center of the rear wheels. The minimum turning radius is achieved when the pivot point is located at the midpoint between the rear wheels. The minimum space required to turn the wheelchair is then determined by the maximum distance from that point to any other point on the wheelchair, usually the front corner of the base or the user's feet hanging off the front of the chair. A similar analysis applies to drive configurations with fixed and differentially driven front wheels and rear caster wheels. The fixed rear wheel and caster front wheel drive configuration is illustrated in **Figure 1.**

To minimize the turning radius for the fixed-wheel, differential-drive configuration, the fixed-drive wheels must be located as close as possible to the geometric center of the chair. For fixed front-wheel-drive chairs, the drive wheels are moved rearward, and for fixed rear-wheel-drive chairs, the rear wheels are moved forward. Several commercially available power chairs have achieved reduced turning radii using this approach: the Quickie P200 series (Sunrise, Longmont, CO), a fixed rear-wheel-drive model, and two front-wheel-drive chairs, the Jazzy® series (Pride Health Care Inc., Exter, PA) and the Action Ranger II Storm series (Invacare Corp., Elyria, OH). Another benefit of locating the drive wheels close to the geometric center of the chair is that a larger portion of the total weight of the wheelchair is borne by the drive wheels and less by the caster

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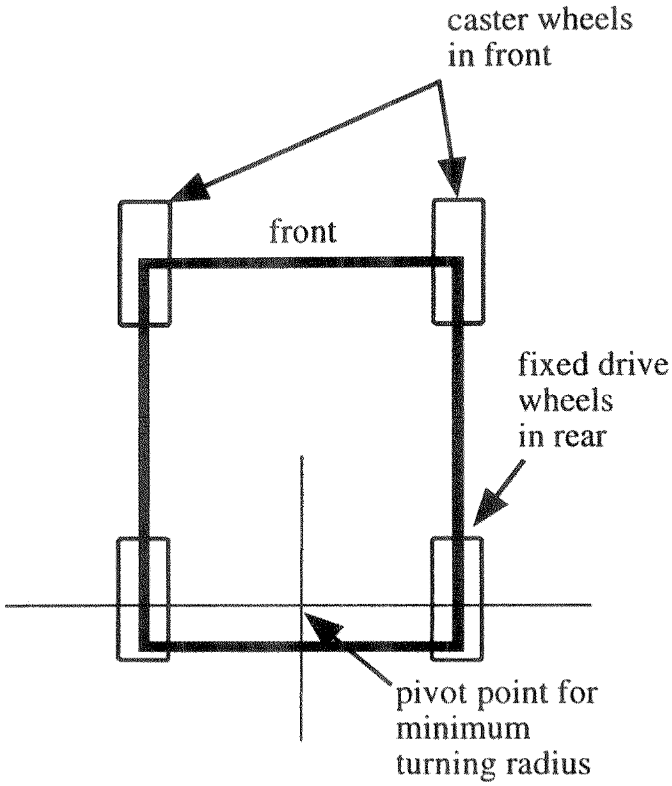

Figure 1.
Fixed rear-wheel differential drive configuration.

wheels. The greater the weight borne by the caster wheels, the more difficult it is to change directions when caster wheels must reverse directions and rotate through 180°. The approach, however, causes the designer to take extraordinary steps to provide stability. Typically, stability is achieved by counterbalancing the user's mass over and in front of the main drive wheels with the mass of the batteries behind the main drive wheels. It may be necessary to provide caster or sprung wheels in the rear of the chair to avoid tipping backward while accelerating forward. The addition of these extra wheels, if small, may also compromise the chair's ability to climb low obstacles.

An alternate approach to minimizing the turning radius is to steer all four wheels; this avoids the problems associated with caster wheels, yet retains minimum turning radius and maximizes stability. Added benefits of four-wheel steering are the tracking of front and rear wheels along the same path and enhanced obstacle climbing capability.

The challenge in designing a mechanical four-wheel steering mechanism is to design a device with the ability to turn each wheel through 180° while minimizing Ackerman errors (misalignment of the

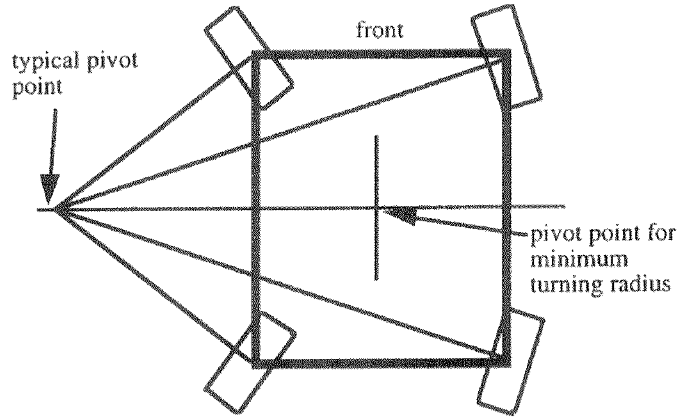

Figure 2. Wheel alignment for four-wheel steering about a single pivot point.

wheels). Ackerman steering linkages, such as those used in automobiles, owe their simple design to the relatively small turning angles required by that type of vehicle. For highly maneuverable wheelchairs, the range of steering angle is much greater, and the wheels must maintain proper alignment over that entire range to avoid undesirable scrubbing when the wheelchair moves. Scrubbing results in excessive tire wear, wrinkling of carpets, and/or undesirable tire noise.

The wheels are properly aligned whenever lines projected from the axis of each intersect at a single point. In four-wheel steering configured for minimum turning radius, this point lies on a line between the front and rear wheels running perpendicular to the fore-aft direction of the base, as illustrated in **Figure 2.** In two-wheel steering, the perpendicular bisectors of the front steered wheels intersect at a point along the line through the centers of the fixed rear wheels.

Another significant advantage of four-wheel steering over two-wheel differentially driven and two-wheel steering is that in the four-wheel configuration, the rear wheels track the front wheels. This is not the case when either the front or rear wheels are fixed. What this means to the user is that when the front of the wheelchair clears a corner, the rear will also clear, if course direction is not changed. The problem is analogous to that facing automobile drivers when they attempt to enter a parking space head in between two other cars, or the one tractor trailer drivers have making turns at right angle intersections. In both situations, the drivers are required to make course corrections during the maneuver to avoid collisions with the obstacles on the inside of the turn. In other words, course corrections must be made to avoid clipping the corner.

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A disadvantage of steering all four wheels is the restriction placed on the power delivery to the drive wheels. Two possible drive configurations are either to mount the motors directly onto the wheels and configure the power base to allow for rotation of the entire motor and wheel assembly, or to deliver power to each of the steered wheels through a right-angle drive assembly along the wheel's turning axis. In either case, power delivery is more cumbersome than to a fixed wheel. In our protoype, we have choosen the first option, direct motor mounting.

METHODS

Design Alternatives

The problems associated with designing a complicated mechanical linkage to achieve four wheel steering can be circumvented using individual computer-controlled steering actuators on each wheel. However, the cost of such a system is likely to be higher than that of a mechanical system, due to the need for three additional actuators and three additional channels of control. The specific design objectives for this project were to develop and evaluate a four-wheel steering mechanism, driven by a single actuator and achieving minimal misalignment over the entire range of steering angles. Although the prototype system implements four-wheel steering, two-wheel steering could be achieved with only a slight modification of the design methods.

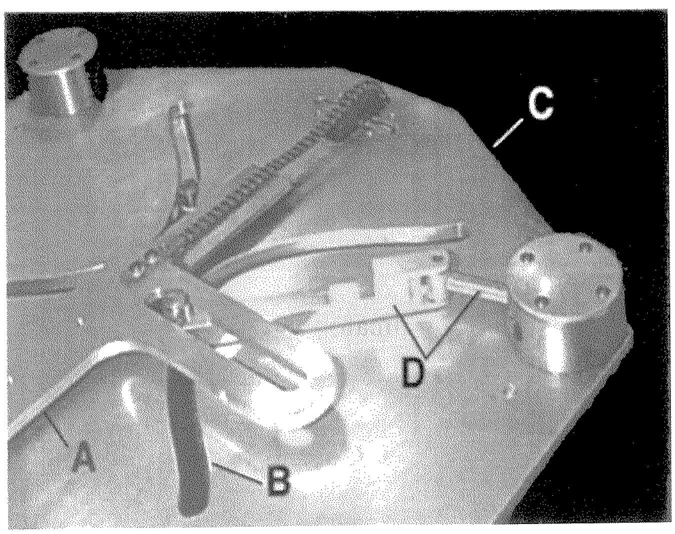

Figure 3.
Section of steering linkage shows (A) sliding member, (B) cam follower slot, (C) flat plate, (D) link members.

A photograph showing a section of the prototype steering linkage is shown in **Figure 3.** The complete linkage consists of two sliding members (A), four cam follower slots (B) cut into a flat plate (C), and two links (D) for each wheel.

The initial design was achieved using graphical methods in a CAD program (CadKey, Inc., Windsor, CT). Subsequent analysis of the graphical methods resulted in the formation of a general mathematical description that allowed for the cam follower slot to be determined given arbitrary link lengths and vehicle dimensions. Using the model, two prototype linkages were developed. A full-size physical model of just one of the four sections of the mechanism (i.e., the linkage section necessary to steer one wheel) was constructed to investigate the feasibility of manufacturing the device. Based on positive results from that exercise, a full-scale working prototype integrated into a wheelchair power base was designed and constructed so that evaluation of the concept could be completed under actual operating conditions.

Proper alignment of the wheels is maintained to avoid undesirable scrubbing of the wheels as the vehicle turns. To maintain alignment, the steering angle on each wheel must be tangent to concentric circles. In the case of the four-wheel steered vehicle, the inside wheels (i.e., the wheels on the right during a right turn and those on the left during a left turn) will be traveling along the path described by a circle with radius r_1 (circle 1 in **Figure 4**) while the outside wheels travel along a circle with the longer radius r_2 (circle 2 in **Figure 4**). The turning rate of the vehicle increases as those radii shorten and the center point of the circles moves toward the center of the vehicle along its midline. Maximum turning rate is achieved when the centers of the circles coincide with the center of the vehicle. For the vehicle to have full turning range, that is, have the ability to rotate about its center in either direction, each wheel must be free to rotate through 180°. Proper alignment is maintained throughout the 180° range if

$$q_L = -\,\mathrm{ArcTan2}\left(\mathrm{Cot}\left(q_S - 2\,\frac{\text{wheelbase}}{\text{track length}}\right)\right) \qquad [1]$$

where Q_L and Q_S are the angles of the wheels on the inside and outside wheels, respectively.

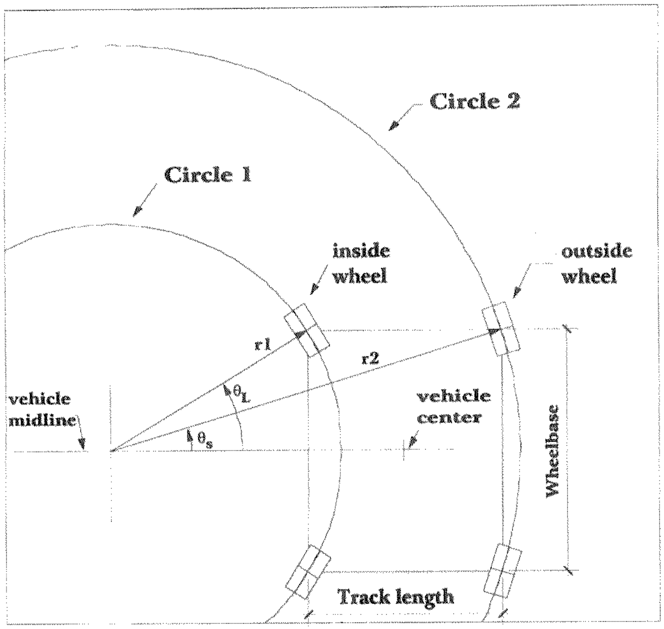

Figure 4.
Wheel alignment constraints for four-wheel steering.

The steering linkage provides proper alignment of the wheels through the shape of the cam path. Furthermore, the cam path is constrained to be symmetric about its midline, so that there is a linear relationship between the translation along the path in the fore and aft direction and the turning motion of the inside and outside wheels of the vehicle. Symmetry of the cam path allows for the use of a single, linear motion steering actuator to drive the steering motion of all four wheels.

The shape and location of the cam path is determined by the wheelbase and track length of the vehicle and the specification of the lengths of members linking the cams to the wheel spindles. It is also necessary to specify the maximum deviation in angle between the two links from 90°. An arbitrary point on the cam path (x,y) is determined by solving the equation

$$x_{midpoint} = x_a - \frac{x_a - x_b}{2} \qquad [2]$$

for y in terms of a_x, a_y, b_x, and b_y

where

$$x_a = a_x - \sqrt{r^2 - (y - a_y)^2}$$

$$x_b = b_x - \sqrt{r^2 - (y - b_y)^2}$$

r is the length of the link between the cam and crank arm.
$x_{midpoint}$ is determined by the specification of the constraint on the angle between the links at the extreme positions. The method for computing $x_{midpoint}$ follows.
(a_x,a_y) and (b_x,b_y) are coordinates of points on the circular path of the end of the crank arm corresponding to the link end positions of the inside and outside wheels, respectively. x_a is the x coordinate of the point on the cam path corresponding to the location of the end of the crank arm (a_x,a_y).
x_b is the x coordinate of the point on the cam path corresponding to the location of the end of the crank arm (b_x,b_y).
y is the y coordinate of the point on the cam path and is the same for the a and b points due to the constraint on the geometry requiring linear motion of the actuator.

The reference coordinate system is centered at the wheel spindle with the y axis parallel to the side of the vehicle and pointed toward the front

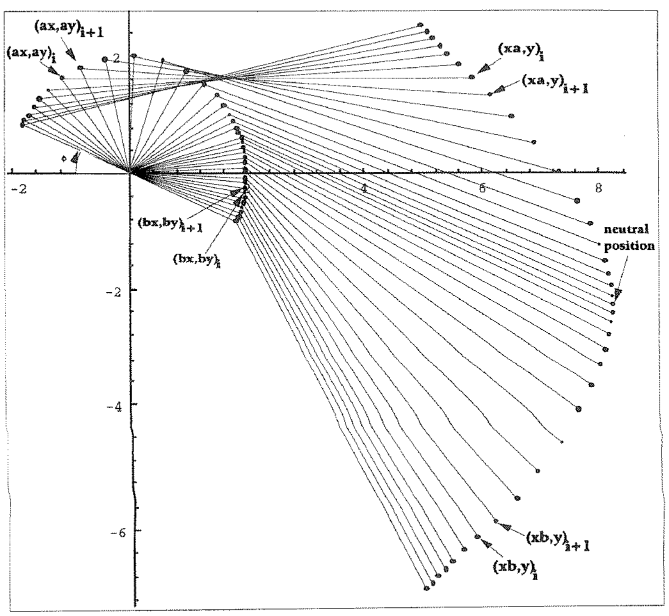

Figure 5.
A series of linkage positions showing the correspondence between the endpoints of each member in the steering linkage.

of the vehicle.

To generate a cam path given the wheelbase, B, the track length, L, the crank arm length, r_c, and the crank arm to cam link length, r, we generated a series of points (a_x,a_y) and (b_x,b_y) on the circular path described by the path of the crank arm where

$$\begin{aligned} a_x &= r_c \operatorname{Sin}(q_s + f) \\ a_y &= r_c \operatorname{Cos}(q_s + f) \\ b_x &= r_c \operatorname{Sin}(q_L + f) \\ b_y &= r_c \operatorname{Cos}(q_s + f) \end{aligned} \qquad [3]$$

and

$$q_L = -\operatorname{ArcTan2}\left(\operatorname{Cot}\left(q_s - 2\,\tfrac{B}{L}\right)\right) \quad [4]$$

f is the angular offset of the crank arm when the wheel is pointed in the neutral position.

The use the solution for y from Equation 2 and compute the points on the cam path, $(x_a,y)_i$, corresponding to the points $(a_x,a_y)_i$ and the points $(x_b,y)_i$, corresponding to the points $(b_x,b_y)_i$ (see **Figure 5**). This solution can also be used to generate a linkage that steers the two front wheels and assumes that the rear wheels are fixed. For this condition, substitute 2B for B in Equation 4, and everything else remains the same.

RESULTS

Evaluation of Static Forces

The losses in the linkage were estimated using a static analysis of torques and forces. The force applied to the sliding member of the linkage was determined as a function of the torque on each wheel for operating points throughout the full range of motion. The result for the linkage dimensions of a 7.62 cm lower member, 15.24 cm upper member, 50.8 cm wheelbase and 45.72 cm track is shown in **Figure 6**. The curve in the figure estimates the sum of linear force required on the sliding member of the linkage per unit torque on the wheels (the sum required to turn all four wheels) as a function of the angle of the inside wheel relative to the straight ahead null position. As the near wheel moves through 45°, the outside wheel moves through 135° to avoid misalignment. At the extreme positions, the perpendicular bisectors of each wheel intersect one another at the geometrical center of the wheelchair base. This analysis demonstrates that there is not any significant loss of mechanical advantage between actuator force and resulting torque on the wheels.

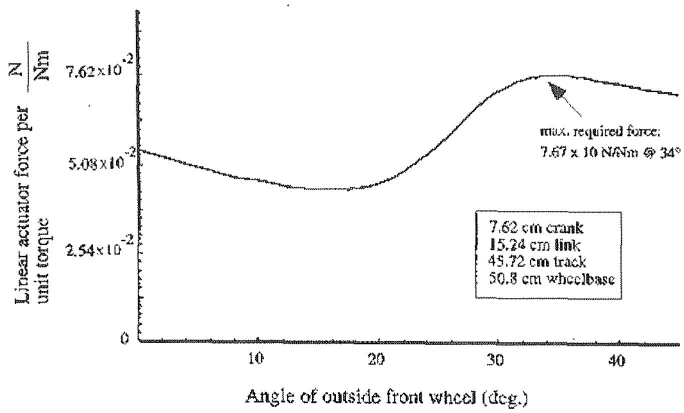

Figure 6.
Relationship between linear actuator force and steering torque.

DISCUSSION

Control Issues

The use of four-wheel steering in wheelchairs introduces a dilemma for the control of that vehicle. Optimum performance is likely attained when the wheels can be left at arbitrary, but known, steering angles while the chair is idle. Under these conditions the driver knows in which direction the chair will initially go and there is no delay in initiating a move. However, making the direction of the wheels known to the driver while the chair is at rest requires the driver to either visually inspect the wheels or obtain the direction information through some other feedback mechanism. Three options come to mind: 1) a visual display on the controller panel; 2) tactile feedback through the control stick using a rotation about either the unused vertical axis or a rotation about the steering axis; and 3) no feedback at all. Although no solution is ideal, a rotation of the stick seems more desirable from the user's perspective because it will not require reading a display, thereby not diverting his or her attention away from the environment. The rotation option is likely more complex and expensive to implement. The third option, no feedback at all, will require the driver to sense the wheel direction by sensing the direction of travel once motion is initiated; this option is likely to be problematic in confined spaces.

The other alternative for control of the vehicle is to program the controller to self-center the wheels each time the chair stops. This solution is also less than ideal. In this configuration, there will be a delay between the time when the user steers the wheels and when the chair is able to travel in the desired direction. If there is no direction feedback for the wheels, the user is required to perform a visual inspection of the wheel direction or sense the direction after initiating a move by observing the direction of travel.

Drive Wheel Options

In the prototype used to evaluate the steering linkage, all four wheels are powered. The range of options available are to power both rear wheels, power both front wheels, and power one rear and one front wheel on opposite sides of the vehicle. Powering all wheels gives maximum performance, and, since each wheel on the same side of the vehicle travels at the same velocity, four completely independent channels of control are not necessary. If the drive wheels are operated open loop, only two channels are required. Either of the other two options requires two independent control channels. The advantage of powering one front and one rear wheel is to retain the ability of the vehicle to climb over low obstacles while traveling either forward or backward, while minimizing the control requirements and the cost of motor drives.

CONCLUSIONS

An innovative feature of this steering linkage design is its ability to drive all four (or two) wheels using a single steering actuator. Its successful implementation will allow for the development of a four-wheel, steered power base with maximum maneuverability, uncompromised static stability, front- and rear-wheel tracking, and optimum obstacle climbing capability.

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