Development of a novel robust custom canine orthotic wheelchair for coordinating object climbing and body tilt motions

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ABSTRACT
This paper is inspired by the four-legged chihuahua Heidi, who suffers erosive immune polyarthritis, resulting in difficulty walking. Available dog wheelchairs are expensive and lack abilities of overcoming rugged terrains or climbing over curbs/obstacles in the environment. They are also stiff, bulky and heavy, thus constraining the dog's healthy movements and not allowing for tilting the dog's body during sniffing and sitting. To alleviate these issues a novel type of low-cost, supporting orthotic wheelchair suitable for small-sized dogs is designed, manufactured and tested. Ongoing testing and analysis show that the body trajectories of the dog while using the wheelchair were not crippled and within 2% standard deviation compared to the natural healthy trajectories enabling the desired repetitive physiological gait and curb climbing. The comparison between the sit and sniff trajectories from a healthy canine compared to those of the disabled canine while on the wheelchair show between 10% and 12.5% error. The authors believe that the latter is partially caused by some of the dog's uncontrolled movements due to Heidi's condition. Although it might require some future motor learning for the canine to better control the sniff/sit patterns, the kinematic task specification and the incorporation of planar parallel six-bar linkages into canines’ orthotic wheelchairs is sufficient for coordinating multiple motions, such as walking, climbing, sniffing and sitting.

INTRODUCTION
Available dog wheelchairs are expensive and lack abilities of overcoming rugged terrains or climbing over curbs/obstacles in the environment [1], [2], [3]. They are also stiff, bulky and heavy, thus constraining the dog's healthy movements and not allowing for tilting the dog’s body during both sniffing and sitting (see Figure 1). To alleviate these issues a novel type of low-cost, supporting orthotic wheelchair suitable for small-sized dogs is designed, based on current results on kinematic synthesis of mechanisms based on velocity and acceleration specifications compatible to mechanism-object/environment contact and curvature constraints [4-11]. To show the applicability of the proposed technique, a prototype of the wheelchair was manufactured and tested.

To understand the key parameters that needed to be taken into account during the canine wheelchair design and analysis, the authors studied the biomechanics of canine motion and mobility concerns [12]. Specifically, experimental data from a Light-emitting diode (LED) attached to the body of a healthy canine, walking at 0.55 m/s on a treadmill, sitting, sniffing and climbing stairs was obtained (see Figure 2). The data analysis supported the idea that quadrupeds habitually power locomotion with their hind-limbs [13]. The analysis also revealed that the dog mechanics of walking resembles a passive stiff-limbed four bar linkage model, which is in agreement with existing literature [14], [15]. In what follows we describe the development of a novel wearable orthotic wheelchair that incorporates two mirrored four bar linkages connected through a rigid link into a six-bar linkage and attached...
on each side of the canine's body was developed. The four-bar linkages are able to obtain the desired curb/obstacle climbing motion, while the resulting six bar linkage provides the desired body sit-sniff tilt.

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Specifically, the goal of the wheelchair is to allow for (i) increased stability/decreased overturn moment, by keeping the center of the wheel motion close to a straight line and (ii) increased climbing capacity of more than one time the wheel diameter, to allow Heidi to go over curbs. Note that in four-wheel drive vehicles, obstacle limit is generally half of the wheel diameter; however it is possible to pass over this height by pushing the driving wheel to the obstacle, which is called climbing. Although obstacle geometries can vary, the most difficult geometry which can be climbed by a wheeled vehicle is a stair-type rectangular obstacle. If the surface friction of an obstacle is not enough to climb, the obstacle force on the wheel can reach high values. A solution for this problem is the use of a linear motion suspension where obstacle reaction force cannot create any moment. The climbing task consisted of curbs with a height of up to 7.2 cm to allow Heidi to successfully overcome the existing obstacles along her daily walks and the wheel diameter was chosen to be 4.8 cm without taking into account the soft rubber tire with thickness of about 1 cm. As the canine powers the wheelchair with their hind-limbs and starts climbing, the wheel should keep in contact with the curb throughout the climbing motion. Thus the task consists of one wheel-curb contact position, located in the middle of two sub-motions. The first contact sub-motion is when the wheel is on the ground and is defined as a close to the vertical motion which starts at the initial contact of the wheel and the curb, i.e. at the height of the wheel center. This causes a horizontal reaction force on the wheel center related to the vertical motion instant center. To ensure that the center of the wheel motion is close to a straight line and at the same time the wheel follows the curb curvature, the second sub-motion is defined as a rotation about a point located at the top/edge of the curb, with an instant center at the edge/the origin of the second sub-motion. Thus, the task for the canine wheelchair consists of one contact location, defined by two contact sub-motions each of which consisting of two velocities and two accelerations (see Table 1 and Figure 1).

The addition of requirements on the accelerations relates to considerations on the local motions of the interaction and allows for an accurate definition of the task in the vicinity of the contact.

### Table 1. The task data for the synthesis of the RR chain.

<table>
<thead>
<tr>
<th>Posit.</th>
<th>Submotions($\phi, d_1, d_2$)</th>
<th>Vel. Data</th>
<th>Accel. Date</th>
<th>$V_P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 4, 4,8)</td>
<td>(0, 3.2, 2.4)</td>
<td>(1, 0.78, 1.78)</td>
<td>(0, 1.95, 4.67)</td>
<td>(1.33, 3.18)</td>
</tr>
<tr>
<td>-</td>
<td>(0, 3.5, 7.2)</td>
<td>(1, -0.2, 0)</td>
<td>(0, -0.17, 0.01)</td>
<td>(3.5, 7.1)</td>
</tr>
</tbody>
</table>

The obtained velocities and accelerations are then directly incorporated into the synthesis task formulation to provide design equations, which are solved in order for the mechanism(s) to be able to realize the desired multi-directional contact task. Four real solutions were obtained, from which solutions 2 and 4 in Table 2 were chosen for the four-bar input and output link dimensions. Thus, the obtained linkage has an input and output link dimensions a= 2.54 cm, b= 5.11 cm, a ground link dimension g= 2.5 cm and a coupler length h= 5.05 cm.

### Table 2. The obtained four real solutions from the synthesis of the RR chain.

<table>
<thead>
<tr>
<th>Solution</th>
<th>$G = (x, y)$(cm)</th>
<th>$W = (x, y)$(cm)</th>
<th>$R$(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-10.47, 5.75)</td>
<td>(5.07, 2.37)</td>
<td>15.91</td>
</tr>
<tr>
<td>2</td>
<td>(-1.31, 4.81)</td>
<td>(3.04, 2.13)</td>
<td>5.11</td>
</tr>
<tr>
<td>3</td>
<td>(1.67, 1.42)</td>
<td>(2.14, -1.01)</td>
<td>2.48</td>
</tr>
<tr>
<td>4</td>
<td>(3.26, 7.87)</td>
<td>(2.29, 5.52)</td>
<td>2.54</td>
</tr>
</tbody>
</table>
Figure 3 shows the chosen design that best fits the requirements, based on the climbing capacity of about one time the wheel diameter. Joint angle, angular velocities and angular acceleration interpolation, adapted from [16] with small modifications, results in the desired close to the linear trajectory, shown in Figure 2.

As a next step, two identical four-bar linkages were rigidly connected into a six-bar, where one of the four-bar linkages is a mirror image of the other. While assembling the two four-bar linkages, special attention was given to achieving a six bar tilt that is as close as possible to the natural sniff-sit tilt motion capture data acquired from the healthy canine. A CAD drawing of the resulting wheelchair coordinating the desired sit-sniff tilt and climb abilities can be seen in Figure 4.

Figure 4. CAD drawing of the passive wheelchair with traced body sniff-sit tilt, as well as front and rear wheel climbing trajectories.

Figure 5 shows the 3D printed prototype of the wheelchair. While powered by the canine’s hind-limbs, the wheelchair is able to climb stairs with sizes up to two and a half times the wheel diameter (see Figure 6).
EXPERIMENTAL TESTING AND RESULTS

The obtained healthy dog walking, sniffing and sitting trajectories were compared with those of the disabled canine while using the wheelchair. Ongoing testing and analysis show that the body trajectories of the dog while using the wheelchair were not crippled and within 2% standard deviation compared to the natural healthy trajectories enabling the desired repetitive physiological gait and curb climbing (see Figure 7).

The comparison between the sit and sniff natural trajectories with those of the canine wearing the wheelchair show between 10% and 12.5% error. The authors believe that the latter is partially caused by some of the dog’s uncontrolled movements due to Heidi’s condition. Although it might require some future motor learning in order for the canine to better control the sniff/sit patterns, the kinematic task specification and the incorporation of planar parallel six-bar linkages into canines’ orthotic wheelchairs is sufficient for coordinating multiple motions, such as walking, climbing, sniffing and sitting.

CONCLUSIONS

Available dog wheelchairs are expensive and lack abilities of overcoming rugged terrains or climbing over curbs/obstacles in the environment. They are also stiff, bulky and heavy, thus constraining dog’s healthy movements and not allowing for tilting the dog’s body during sniffing and sitting. To alleviate these issues a novel type of low-cost, supporting orthotic wheelchair suitable for small-sized dogs is designed, manufactured and tested. Ongoing testing and analysis show that the body trajectories of the dog while using the wheelchair were not crippled and within $2\%$ standard deviation compared to the natural healthy trajectories enabling the desired repetitive physiological gait and curb climbing. The comparison between the sit and sniff trajectories from a healthy canine compared to those of the disabled canine while on the wheelchair show between 10% and 12.5% error. The authors believe that the latter is partially caused by some of the dog’s uncontrolled movements due to Heidi’s condition. Although it might require some future motor learning in order for the canine to better control the sniff/sit patterns, the kinematic task specification and the incorporation of planar parallel six-bar linkages into canines’ orthotic wheelchairs is sufficient for coordinating multiple motions, such as walking, climbing, sniffing and sitting. Future research includes the development of customizable wheelchair that can be worn by dogs with different sizes.
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