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Finite Element Analysis of Forearm Crutches During Gait in Children with Myelomeningocele

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***Abstract*— A finite element analysis of a commercial forearm crutch for children during gait is presented. The geometric features of the crutch structure were acquired and modeled. The finite element model was created using shell elements based on the frame surfaces. Linear elastic material properties for aluminum alloy were utilized. Upper extremity kinetic data from reciprocal and swing-through gait patterns were applied to the model as boundary conditions and loads. Stress distributions during two gait patterns were determined. Stress distributions during swing-through gait were found to be statistically greater than those during reciprocal gait (p = 0.01). This work provides novel quantitative data to improve crutch design and stimulate further analyses of upper extremity joint loads during forearm crutch-assisted gait in children with myelomeningocele (spina bifida).**

Keywords—Finite element analysis, crutch, gait, biomechanics, myelomeningocele.

I. Introduction

Persons with myelomeningocele (MM) often use forearm crutches for ambulation. These mobility aids may place them at risk for development of upper limb pathologies. Current literature demonstrates that long-term crutch usage may result in upper limb syndromes, such as destructive shoulder arthropathy, degenerative arthritis of the shoulder and wrist, and carpal tunnel syndrome (CTS) [1, 2]. Repetitive impulse loading combined with prolonged wrist extension and radial deviation are proposed risk factors associated with the use of crutches [3, 4]. Klimaitis and colleagues report that bearing weight through the upper limbs may hasten the development of degenerative arthritis in the shoulder, possibly by contributing to mechanical disruption of the rotator cuff [5]. Also, large superiorly directed weight-bearing forces may potentially threaten glenohumeral joint integrity, as translation of the humeral head and subsequent impingement of subacromial structures may occur, if forces are not matched by an appropriate response of the rotator cuff and thoracohumeral depressor musculature [6, 7]. An association between the development of CTS and the use of assistive devices by patients has also been described [3, 4, 8]. Clinically, patients using forearm crutches have reported hand pain and sensory disturbances, which are symptoms associated with CTS [3].

Many children with MM develop impairments, which may lead to later conditions such as osteoarthritis and inflammatory polyarthropathies from long-term crutch usage. Therefore, design of the forearm crutch is a crucial element in determining the quality of life of these children. There is, unfortunately, only limited information on upper extremity dynamics during crutch-assisted gait. We hypothesize that upper extremity (UE) crutch stresses will be greater during the commonly used swing-through forearm crutch-assisted gait pattern than during reciprocal crutch-assisted gait pattern. This study may provide valuable information for improving crutch designs and more relevant biomechanical modeling of the upper extremity joints during crutch-assisted gait.

II. Methodology

Nine subjects with L3-L4 level myelodysplasia, aged 11.1 ± 3.8 years, participated in the research study. Subjects' mean (range) height and weight was 1.3 m (1.0-1.7 m) and 42.6 kg (17.2-83.9 kg), respectively. All subjects were recruited from Shriners Hospital in Chicago, Illinois. Crutches were instrumented with 6-axis dynamometers (AMTI), just above the tip, to measure applied reaction forces and reaction moments three-dimensionally along the Cartesian X, Y, and Z-axes. Motion analysis was conducted to evaluate upper extremity force dynamics using our model with seven rigid body segments and 26 markers [9]. The UE model was previously evaluated by our group for accuracy and precision [10].

Subjects walked with the instrumented bilateral Lofstrand crutches at a self-selected speed along a six-meter walkway until five successful trials were completed for each gait pattern, reciprocal and swing-through. Three-dimensional (3D) motion of the segments was captured using a fourteen-camera Vicon MX motion analysis system. Data were processed using Vicon Workstation V4.6 software to produce 3D coordinates of each marker.

A. Geometry Acquisition and Mesh Generation

The geometry features of the crutch (Walk Easy Inc. Delray Beach, FL) were measured (Fig. 1). The adjustable height (360 mm to 530 mm from grip to floor) was set to 470 mm. The surfaces of frames were created and shell elements were generated from the surfaces using ABAQUS/CAE (Fig. 2).

Fig. 1. Forearm crutch

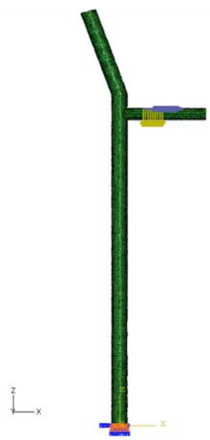

Fig. 2. Forearm crutch with mesh, boundary conditions, and load applied at the handle.

B. Element Type and Material Properties

The model consisted of a total of 8,392 S4 (4-node full integration) and 120 S3 (3-node full integration) shell elements. Thickness of the shell elements was set to 1.5 mm. Five integration points through the thickness were used. Linear elastic material properties of aluminum alloy were specified: Young's modulus E = 69 GPa; Poisson's ratio $\nu = 0.33$.

C. Boundary Conditions and Loads

As a preliminary study, the tip of the crutch was fully constrained to simulate contact with the ground. Forces and moments from kinetic data during reciprocal and swing-through gait patterns were used for comparison purposes (Table 1) [9]. Distributed forces and moments were applied on the top of the crutch's handles to avoid stress concentration. All simulations were carried out in ABAQUS 6.7.

TABLE 1
FORCE AND MOMENT INPUT FROM MOTION ANALYSIS

	Reciprocal Gait		Swing-Through Gait	
Measure	Right	Left	Right	Left
Force (N)	50.9	50.9	89.3	91.4
Moment (Nm)	4.9	4.3	7.6	9.8

III. RESULTS

Stress distributions during reciprocal and swing-through gait load cases were determined (Figs. 3-4). The maximum stresses during both gait patterns are below the yield strength of aluminum (214 MPa). The maximum von Mises stress of 21.2 MPa was found for the left and right crutches during reciprocal gait. Swing-through gait demonstrated significantly higher von Mises stresses of 37.7 MPa (left) and 37.2 MPa (right). The t-test was used to statistically examine two-group differences between reciprocal and swing-through gait stress distribution (p = 0.01).

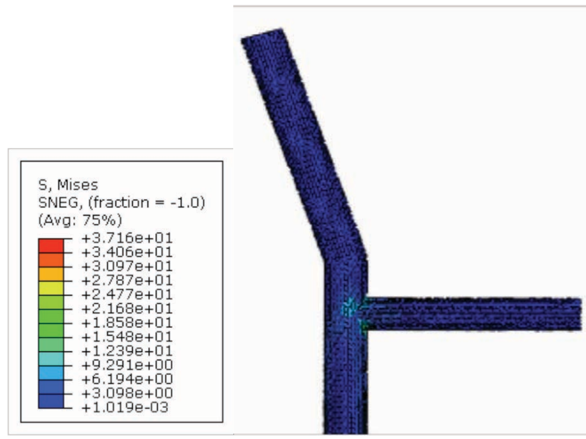

Fig. 3. Stress distributions of the crutch during reciprocal gait.

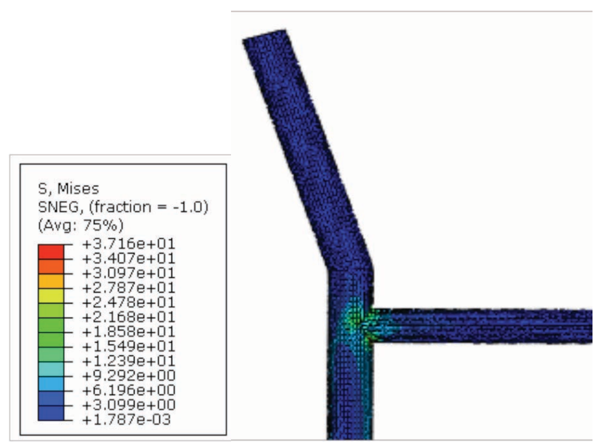

Fig. 4. Stress distributions of the crutch during swing-through gait.

IV. DISCUSSION

Typically, beam elements are used to construct frame structures in finite element models. Although they can demonstrate which component of crutch frames will be affected during gait, a 3D finite element model is required to obtain the explicit stress distribution on the frame, as demonstrated in this study. The maximum stresses during swing-through gait were found to be significantly greater than those during reciprocal gait. This can be attributed to the large force demands placed upon the upper body (53% body weight) during ambulation.

The current model may be readily modified for the simulation of different crutch designs (e.g. force mitigating). Applying distributed loads on the handle surface in the model replicates the forces and moments developed in the realistic scenario. Furthermore, shell-to-solid sub-modeling techniques available in ABAQUS are capable of analyzing the tip of the crutch with a solid element mesh and provide the ability to simulate friction between the crutch tip and ground in future studies. Ultimate design goals include development of a crutch that safely absorbs stress the upper body would otherwise bear, and one which transmits energy through a combination of materials with a physical design that aids the ambulatory process in larger populations of crutch users (i.e. spinal cord injury, spina bifida, cerebral palsy, and osteogenesis imperfecta). Investigated design factors involve force-mitigating elements to reduce the high loads observed during crutch contact, while maintaining stability of the user during ambulation. Mechanical designs including the Maxwell, Kelvin-Voigt, and the Standard Linear Solid models may be appropriate for this application.

V. Conclusion

Finite element analysis was employed to explore the stress distribution of a commercial forearm crutch during assisted-gait in children with myelomeningocele. The maximum stresses during swing-through gait were found to be significantly greater than those during reciprocal gait. This analysis provides insight into the stress distribution of an important ambulatory device used by children with lower extremity weakness who are long-term crutch users. This work may lead to novel crutch designs and serves as the foundation for further analyses of upper extremity dynamics during crutch-assisted gait.

Acknowledgment

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References

[1] S. Lal, "Premature degenerative shoulder changes in spinal cord injury patients," *Spinal Cord,* vol. 36, pp. 186-9, 1998.

[2] K. A. Opila, A. C. Nicol, and J. P. Paul, "Upper limb loadings of gait with crutches," *Journal of Biomechanical Engineering,* vol. 109, pp. 285-90, 1987.

[3] D. A. Sala, L. M. Leva, F. J. Kummer, and A. D. Grant, "Crutch handle design: effect on palmar loads during ambulation," *Archives of Physical Medicine & Rehabilitation,* vol. 79, pp. 1473-6, Nov 1998.

[4] W. P. Waring, 3rd and R. A. Werner, "Clinical management of carpal tunnel syndrome in patients with long-term sequelae of poliomyelitis," *Journal of Hand Surgery - American Volume,* vol. 14, pp. 865-9, Sep 1989.

[5] A. Klimaitis, G. Carroll, and E. Owen, "Rapidly progressive destructive arthropathy of the shoulder--a viewpoint on pathogenesis," *Journal of Rheumatology,* vol. 15, pp. 1859-62, 1988.

[6] C. J. Newsam, A. D. Lee, S. J. Mulroy, J. Perry, C. J. Newsam, A. D. Lee, S. J. Mulroy, and J. Perry, "Shoulder EMG during depression raise in men with spinal cord injury: the influence of lesion level," *Journal of Spinal Cord Medicine,* vol. 26, pp. 59-64, 2003.

[7] N. A. Sharkey, R. A. Marder, N. A. Sharkey, and R. A. Marder, "The rotator cuff opposes superior translation of the humeral head," *American Journal of Sports Medicine,* vol. 23, pp. 270-5, May-Jun 1995.

[8] W. S. Kellner, G. Felsenthal, J. M. Anderson, E. B. Hilton, D. L. Mondell, W. S. Kellner, G. Felsenthal, J. M. Anderson, E. B. Hilton, and D. L. Mondell, "Carpal tunnel syndrome in the nonparetic hands of hemiplegics. Stress-induced by ambulatory assistive devices," *Orthopaedic Review,* vol. 15, pp. 608-11, Sep 1986.

[9] B. A. Slavens, "Biomechanical Assessment of Upper Extremity Dynamics During Lofstrand Crutch-Assisted Gait in Children with Myelomeningocele," in *Biomedical Engineering.* vol. PhD Milwaukee: Marquette University, 2007, p. 190.

[10] B. Hingtgen, J. R. McGuire, M. Wang, and G. F. Harris, " An Upper Extremity Kinematic Model for Evaluation of Hemiparetic Stroke," *Journal of Biomechanics,* vol. 39, pp. 681-688, 2006.