Multi-body Simulation of Cervical Traction Therapy

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論文内容の要旨

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専　攻　計算科学

論文題目（外国語の場合は，その和訳を併記すること。）

Multi-body Simulation of Cervical Traction Therapy

頸椎牽引療法のマルチボディシミュレーション

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Cervical traction therapy has been widely employed in clinical situations and rehabilitation as a non-surgical treatment for the cervical spine. However, due to the complex structure of the cervical spine and the traction parameters, such as traction force, angle and position, involved in the treatment, the mechanism of cervical traction therapy has not been fully understood. The motivation of this research is to better understand the mechanism of the inclined and sitting positions, and to study their relationships with the traction force, angle and the resulting intervertebral separations. We developed a multi-body simulation model that includes the cervical spine and two cervical traction devices which represent the inclined and sitting positions. By using the model, the objective of this research is to compare the intervertebral separations achieved by the two positions when different amount of traction force and traction angle are used. In order to achieve this objective, we performed the following three studies.

Firstly, a multi-body simulation model, namely Model 1, which includes the cervical spine and two traction devices was developed using a physics engine. In the cervical spine part of the model, each intervertebral vertebra was modeled as a rigid body. The intervertebral disc between two adjacent intervertebral vertebrae was modeled by a pair of translational and rotational joints using springs and dampers. The mechanical parameters, such as the range of motion, stiffness and damping coefficients, used to simulate the behavior of the cervical spine were referenced from published literatures (Jager 1996, Horst 2002, Lopik 2007). Model 1 was used to evaluate the inclined position and sitting position on how they affect the intervertebral separations during cervical traction therapy. Traction forces ranged from 60N to 200N and traction angles at 10/20/30/40° were tested. The result showed that the inclined position created greater intervertebral separations than the sitting position in all four traction angles under the same amount of traction force.

Secondly, in order to validate the behaviour of Model 1, laboratory experiment was conducted to acquire radiographic images of the cervical spine from subjects receiving cervical traction in the inclined and sitting positions. Six male subjects were recruited for the experiment. Traction forces from 100N to 160N and traction angles at 10/20/30/40° were used. The experiment results showed that for the three subjects who received cervical traction in both positions, the inclined position was able to achieve greater separations than the sitting position, which agreed with the simulation result of Model 1. The individual responses in the inclined position showed that the amount of posterior separations increases proportionally as traction angle increases, but such behavior was less consistent in the sitting position. The result suggested that cervical traction in the sitting position cannot reliably control the amount of separations using traction angles. Next, simulation result of Model 1 was generated based on the experiment setup and was compared to the experiment result. The behavior of the model was found to be different from the experiment. While the posterior separations in the experiment increased with traction angles in both positions, posterior separations in Model 1 decreased with traction angles. In an attempt to calibrate the model to match with the experiment data, biomechanical parameters including the range of motion, stiffness and damping coefficients in the simulation model were modified. Although the model was able to match the behavior of the experiment result with the modified parameters, their values did not match with the ones reported by the reference literatures. As a result, it indicated that Model 1 was insufficient to accurately simulate the behavior of the cervical spine during cervical traction therapy.

Finally, due to the difference between the behavior of Model 1 and the experiment result, Model 2 was developed. Anterior and posterior horizontal shear movement of the intervertebral discs were added to the model. Instead of using a single translational joint to represent the vertical movement of the discs, two translational joints were used to represent the anterior and posterior vertical movement separately, with the posterior vertical movement representing the resistance force of the posterior ligaments. The simulation result of Model 2 was compared to the experiment data. The inclined and sitting positions was shown to match the overall behavior of the experiment result. Then, the experiment data was further examined. In particular, the posterior separations in the upper and lower spine were compared between the two positions. In the inclined position, an increase in the traction angle increases the posterior separation in lower spine but causes little changes in the upper spine, while similar behavior was not observed in the sitting position. The finding regarding the upper and lower spine from the experiment data was then used to compare the behaviours of Model 1 and Model 2. While Model 1, even with the modified parameters, failed to match the finding, Model 2 was shown to match the behaviour of the upper and lower spine in the experiment data.

Using Model 2, the behavior of cervical spine in relation to body parameter such as hip joint stiffness and the stiffness level at each cervical segment was investigated. By varying the stiffness parameters in the anterior/posterior shear, flexion/extension, and tension/compression, we found that the tension/compression stiffness parameter affects the resulting separations the most. The result also showed that the resulting separation of sitting position was more sensitive to variation in hip joint stiffness than the one of inclined position. The sitting position tends to cause the subject to lose balance during traction, thus leading to undesired changes at large traction angles. In contrast, for inclined position, the resulting separation was less sensitive to variations in hip joint stiffness and the stiffness level at each cervical segment. This finding may help to explain the consistent results among subjects who used inclined traction in the experiment.

In summary, the study compared the inclined and sitting positions using two multi-body simulation models and data from a radiographic experiment. The inclined position was found to be able to achieve greater separations than sitting position. The result also suggested that traction angle could be used to influence the amount of intervertebral separations and such behavior was more consistent in the inclined position. In particular, with the inclined position, traction angle could be used to influence the amount of posterior separations in the lower spine, while keeping the separations constant in the upper spine. The study also investigated the inconsistent nature of the sitting position. Using the simulation model, the sitting position was shown to be more susceptible to variations in the subject's hip joint stiffness.

Future work of this study should focus on gathering more clinical data in the inclined and sitting positions. It would be important to capture radiographic videos of the cervical spine during traction to measure the transformation of each intervertebral discs, since such data will be necessary to validate the timing responses of our simulation model. The effects of body parameters, gender and age of cervical traction patients should be further investigated. By collecting more clinical data regarding the patients, the simulation model can be improved to estimate the intervertebral separations based on patient-specific data. It will help to identify the necessary traction parameters to achieve customized traction. We believe the present model can help clarify the

mechanism of inclined and sitting traction positions, and to promote further research in studying the cervical traction technique.

（別紙１）　　　　　　　　論文審査の結果の要旨

氏名	Wong Lawrence		
論文題目	Multi-body Simulation of Cervical Traction Therapy 和訳：頸椎牽引療法のマルチボディシミュレーション		
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要　　旨

本研究は、頸椎牽引に関する身体筋骨格系と二種類の牽引機器との合成の剛体力学モデルを構築し、各種牽引角度と牽引力で生じた頸椎の変形について計算機シミュレーションと実機実験を行い、二種類の牽引機器による頸椎牽引効果について比較を行った。

頸椎はC1からC7までの７個の頸骨から構成されており、各部位における病変により、呼吸困難、感覚異常、肩こり、手のしびれなど、様々な症状が誘発される。各種症状の軽減を図るために、必要な頸椎部位に必要な量の牽引を精確に行うことが重要である。臨床では、現在一般的に医師の経験による処方で患者の症状に応じた牽引角度と牽引力の設定を行ってきた。ほとんどの臨床応用では、患者が座位姿勢での牽引が行われているが、牽引角度と牽引力により、対象者の上半身も動かされ、結果として、頸椎の必要な部位における期待の牽引が正確に実現できない問題が残されている。この課題を改善するために、座位姿勢を適切な角度で垂直方向に回転し、上半身の変動をできるだけ抑えて牽引する手法が開発されている。

本研究では、上記の二種類の牽引機器による牽引効果について計算機シミュレーションを用いて各種牽引条件での比較検討を行った。具体的には、以下の三つの研究を展開してきた。

まずは、身体筋骨格系と二種類の牽引機器との合成モデルを構築し、各種牽引角度と牽引力で生じた頸椎の変形について計算機シミュレーションを行った。頸椎部位については、剛体と粘弾性要素で結合するモデルで近似し、各頸骨間の結合は直進と回転の二自由度関節で構成していた。各種牽引角度と牽引力で行ったシミュレーションの結果、対象者の座位姿勢を垂直方向で回転した場合の牽引は、頸骨間変位の時間応答に振れがなく、安定した牽引が実現できることを示した。この部分の研究成果は、査読付きの国際論文誌 **J. Biomed. Sci. Eng.**に掲載された。

上の研究で構築したシミュレーションモデルの正確性を検証するために、二種類の牽引機器による牽引実験も行い、６名の被験者による各種牽引角度と牽引力での牽引効果を分析した。その結果、牽引角度の変化により、従来の座位姿勢牽引では頸椎の変位が対象者によって不規則に変化する傾向を示しているが、座位姿勢を回転した場合では、安定した変位の変化を示した。この実験結果により、シミュレーションモデルにおけるパラメータの再調節を行い、実験結果と比較した。この部分の研究成果は、査読付きの国際論文誌 **Open J. Ther. Rehabil.**に掲載されている。

さらに、シミュレーションモデルに利用する粘弾性パラメータと既存の関連する頸椎に関する研究で発表されているデータと照合して、頸椎のモデルの改善を試み、各頸骨間の結合構造を再構築することにより、既存研究論文で発表された頸椎の粘弾性パラメータに則して、上記実験結果と矛盾しないシミュレーション結果を得ることができ、この部分の研究成果は、査読付きの国際学術会議 **IEEE Int. Conf. on ROBIO 2018** で口頭発表された。

本論文は６章で構成されている。

第１章は、本研究の背景、本論文の目的と構成について説明している。

第２章において、本論文の準備として、頸椎の構成や頸椎牽引に関する基礎的な知見を記述している。また、本研究で構築した二種類の牽引機器と身体筋骨格系との合成モデルについて説明している。

第３章では、本研究で構築した合成モデルを用いて、各種牽引角度と牽引力で生じた頸椎変位についてシミュレーションを行い、異なる座位姿勢による牽引変位効果について比較を行った。

第４章では、二種類の牽引機器による牽引実験を行い、６名の被験者による各種牽引角度と牽引力での牽引結果を分析し、それに基づいてシミュレーションにおけるモデルのパラメータ調整を試みた。

第５章は、シミュレーションモデルの各頸骨間の結合構造の改善を試み、既存研究で発表された頸椎の粘弾性パラメータに則して、上記実験結果と矛盾しないシミュレーション結果を得ることを確認した。

最後に第６章は，本論文のまとめと今後の課題について述べている。

氏名	Wong Lawrence

以上で、本論文は、頸椎牽引における異なる座位姿勢での牽引効果について、計算機シミュレータを構築して、実験結果と合わせて詳細に比較検討され、数多くの有益な知見と有益な示唆を与えることができた。よって、提出された論文はシステム情報学研究科学位論文評価基準を満たしており、学位申請者の　Wong Lawrence　は、博士（工学）の学位を得る資格があると認める。