Aus dem Julius Wolff Institut
der Medizinischen Fakultät Charité – Universitätsmedizin Berlin

DISSERTATION

Development and Application of a Three-dimensional Finite Element Model of Spino-pelvic Complex

zur Erlangung des akademischen Grades
Doctor medicinae (Dr. med.)

vorgelegt der Medizinischen Fakultät
Charité – Universitätsmedizin Berlin

von

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Zusammenfassung

Nach einer vollständigen Sakrektomie ist es zur Wiederherstellung des Kraftflusses notwendig, die Verbindung zwischen Lendenwirbelsäule und Becken zu rekonstruieren. Es existieren nur wenige biomechanische Studien, in denen unterschiedliche Methoden der Rekonstruktion verglichen wurden. Das Ziel dieser Studie war es, mit Hilfe von dreidimensionalen Finite-Element-Modellen des Beckens und der Wirbelsäule vier unterschiedliche Methoden der Rekonstruktion nach vollständiger Sakrektomie zu vergleichen. Die folgenden vier Rekonstruktionsmethoden wurden simuliert: eine Sakral-Stab-Rekonstruktion, eine Vier-Stab-Rekonstruktion, eine Beidseitige-Fibulaspan-Rekonstruktion und eine Verbesserte-Verbund-Rekonstruktion. Zur Simulation der Standardlastfälle Stehen, Flexion, Extension, Seitneigung und axiale Rotation wurden eine sogenannte *Geführte Kraft* und ein reines Drehmoment in der jeweiligen Richtung auf die Finite-Element-Modelle mit Rekonstruktion appliziert. Diese Art der Lasten wird häufig in In-vitro-Studien verwendet. Anschließend wurden die in den Modellen berechneten Verformungen sowie die in den Implantaten auftretenden Spannungen berechnet und verglichen. Für die auftretenden Rotationen zwischen dem fünften Lendenwirbel und dem Darmbein sowie für die Abwärtsverschiebung des fünften Lendenwirbels ergab sich folgende, absteigend sortierte Reihenfolge der Rekonstruktionsmethoden: Vier-Stab-Rekonstruktion > Sakral-Stab-Rekonstruktion > Beidseitige-Fibulaspan-Rekonstruktion > Verbesserte-Verbund-Rekonstruktion. Die in den Implantaten auftretenden maximalen Vergleichsspannungen führten zu folgender, absteigend sortierter Reihenfolge: Sakral-Stab-Rekonstruktion > Vier-Stab-Rekonstruktion > Beidseitige-Fibulaspan-Rekonstruktion > Verbesserte-Verbund-Rekonstruktion. Aus mechanischer Sicht zeigt die Verbesserte-Verbund-Rekonstruktion die besten Ergebnisse mit der im Vergleich höchsten Stabilität und kleinsten auftretenden maximalen Vergleichsspannungen. Allerdings müssen bei der Wahl der Rekonstruktionsmethode für einen spezifischen Patienten auch klinische Aspekte berücksichtigt werden.

Diese Dissertation wurde entsprechend der Promotionsordnung vom 3. Dezember 2012 auf der Basis „einer Peer-reviewed-Orginalpublikation als Erstautorin/Erstautor in einer international führenden Fachzeitschrift“ erstellt. In zwei weiteren, bei Fachzeitschriften eingereichten Arbeiten wurde die Eignung des verwendeten Modells sowie der applizierten Lasten begründet und diskutiert. Diese Arbeiten sind nicht Bestandteil dieser Dissertation, wurden aber zur Vollständigkeit in der Publikationsliste aufgeführt.

Schlagwörter: Wirbelsäule, vollständige Sakrektomie, Finite-Elemente-Methode

Abstract

After total sacrectomy, it is mandatory to reconstruct the continuity of the force flow between the lumbar spine and the pelvis. In only few biomechanical analyses different reconstructions were compared. The aim of the study was to compare four different reconstruction methods after total sacrectomy using a three-dimensional finite element model of spino-pelvic complex. A sacral-rod reconstruction, a four-rod reconstruction, a bilateral fibular flaps reconstruction and an improved compound reconstruction were simulated. A follower load and a pure moment which are common in *in vitro* studies were applied to the reconstruction models to simulate standing, flexion, extension, lateral bending and axial rotation of the spine. The deformation of the models and the stresses in the implants were calculated and evaluated. The decreasing order of the rotations between L5 vertebra and ilium as well as of the L5 shift-down displacement for the studied reconstruction methods was: four-rod reconstruction > sacral-rod reconstruction > bilateral fibular flaps reconstruction > improved compound reconstruction. The decreasing order of the maximum von Mises stress in the implants was: sacral-rod reconstruction > four-rod reconstruction > bilateral fibular flaps reconstruction > improved compound reconstruction. From the mechanical point of view, the improved compound reconstruction is superior to the other methods studied here as it shows the highest stability and the lowest maximum equivalent stresses. However, clinical aspects must also be regarded when choosing a reconstruction method for a specific patient.

The dissertation was created based on the Thesis Regulation dated December 3, 2012, requiring "one peer-reviewed original publication as the first author in a leading international professional journal". In two additional manuscripts submitted to peer-reviewed journals the applicability of the used model and of the commonly used load application method were justified. They are not part of this dissertation, but cited in the list of publications for completeness.

Key Words: Spine; Total sacrectomy; Finite element method

Affidavit

I, Rui Zhu, certify under penalty of perjury by my own signature that I have submitted the thesis on the topic *Development and application of a three-dimensional finite element model of spino-pelvic complex*. I wrote this thesis independently and without assistance from third parties, I used no other aids than the listed sources and resources.

All points based literally or in spirit on publications or presentations of other authors are, as such, in proper citations (see "uniform requirements for manuscripts (URM)" the ICMJE www.icmje.org) indicated. The section on methodology (in particular practical work, laboratory requirements, statistical processing) and results (in particular images, graphics and tables) corresponds to the URM (s.o) and are answered by me. My contribution in the selected publication for this dissertation corresponds to those that are specified in the following joint declaration with the responsible person and supervisor.

The importance of this affidavit and the criminal consequences of a false affidavit (section 156,161 of the Criminal Code) are known to me and I understand the rights and responsibilities stated therein.

Date   Signature

Detailed Declaration of Contribution

Rui Zhu had the following share in the publication:

Zhu R, Cheng LM, Yu Y, Zander T, Chen B and Rohlmann A, Comparison of four reconstruction methods after total sacrectomy: A finite element study, Clin Biomech (Bristol, Avon), 2012 Oct, 27(8): 771-6

Contribution in detail (please explain in detail):

(1) Rui Zhu did more than 95% of the work in the current study regarding *reviewing literature*:

After total sacrectomy, it is mandatory to reconstruct the continuity between the lumbar spine and the pelvis. Rui Zhu jointed a cadaveric experiment focusing on different reconstruction methods after total sacrectomy. However, in that study the mechanical stability was only investigated for the loading case standing. Elaborated finite element analyses allow a more detailed mechanical analysis and the investigation of several reconstruction designs under various loading cases. Therefore, Rui Zhu decided to use this scientific tool to investigate the mechanical stability of different reconstructions methods after total sacrectomy. After a detailed literature review, several reconstructions methods after total sacrectomy were identified. However, up to date only a few biomechanical analyses compared different reconstructions methods. A biomechanical optimal method has not been established, partly due to the lack of biomechanical evidence. Currently, there is a lack of consolidated knowledge regarding the stability and the risk of implant failure for different reconstruction methods.

(2) Rui Zhu did more than 80% of the work of in the current study regarding *designing the study*:

Based on the existing literature of different biomechanical studies and clinical case reports, the present study was designed. Four different reconstruction methods after total sacrectomy were involved. The stability of reconstruction method was evaluated by the rotation between 5th lumbar vertebra (L5) and the ilium and the L5 shift-down displacement. Relative risk of implant breakage was evaluated by the relative maximum von Mises stress in the implants. Finite element models were used to calculate the above mentioned parameters for elementary activities of the spine: standing, flexion, extension, lateral bending and axial rotation. Rui Zhu integrated the opinions of all co-authors and designed the study.

(3) Rui Zhu did 100% of the work in the current study regarding *developing the pelvic finite element model*:

A nonlinear FE model of lumbar spine was used. This model was created and validated by the Julius Wolff Institut, Charité – Universitätsmedizin Berlin. A rigid pelvic model which was taken from the data of Virtual Human was meshed by tetrahedron elements. Homogeneous elastic material properties were assigned. This pelvic model was added into the lumbar model, in order to provide the anatomical structures for the implants in different reconstructions. The sensitivities of the material properties used for pelvis were additionally studied to increase the reliability of the calculated stress.

(4) Rui Zhu did 100% of the work in the current study regarding *simulating all different reconstructions after total sacrectomy*:

Four different reconstruction methods after total sacrectomy were simulated. Detailed pieces of information regarding the surgical procedure and the biomechanical experiments were gathered from literature. The spatial locations of the implants were checked from a clinical point of view. All parameters such as diameters, elastic modulus and Poisson's ratio for the implants were collected from literature. The mesh size of the implant was tested to ensure the convergence of the finite element analyses. The numbers of the beam elements which simulate contact between screws and bone were tested.

(5) Rui Zhu did 100% of the work in the current study regarding *validation*:

For validation purposes, the same loads and the same boundary conditions as used in the cadaveric study were applied. The same parameters as in the cadaveric study - rotation between L5 and the ilium and the L5 shift-down displacement - were calculated and compared with each other.

(6) Rui Zhu did 90% of the work in the current study regarding *carrying out calculations and analysing data*:

Follower loads and pure moments from literature were applied to simulate elementary activities of the spine: standing, flexion, extension, lateral bending and axial rotation. Parameters regarding stability and relative risk of implant breakage were calculated and gathered. The results were discussed by all co-authors.

(7) Rui Zhu did 80% in the current study regarding *Drafting and revising the article*:

Rui Zhu wrote the manuscript and discussed it with all co-authors. During revision process, the questions from the reviewers were answered and the manuscript was revised following the reviewers' suggestions.

Signature, date and stamp of the supervising University teacher

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Signature of the doctoral candidate

____

Printed Copy of Selected Publication:

Zhu R, Cheng LM, Yu Y, Zander T, Chen B and Rohlmann A. Comparison of four reconstruction methods after total sacrectomy: A finite element study. *Clin Biomech (Bristol, Avon), 2012 Oct, 27(8): 771-6.* DOI:10.1016/j.clinbiomech.2012.05.008

(5-year IF = 2.468; IF (2011) = 2.071; Eigen factor = 0.01099)

The journal's relative rating

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☐	3	J BONE JOINT SURG AM	0021-9355	34294	3.272	4.289	0.303	310	>10.0	0.03435	0.937
☐	4	AM J SPORT MED	0363-5465	14958	3.792	4.427	0.626	313	7.6	0.02732	1.159
☐	5	OSTEOARTHR CARTILAGE	1063-4584	7723	3.904	4.365	0.812	170	5.2	0.02327	1.279
☐	6	J ORTHOP RES	0736-0266	10618	2.811	3.197	0.480	281	8.3	0.02115	1.007
☐	7	EUR SPINE J	0940-6719	5658	1.965	2.524	0.219	343	5.3	0.01955	0.799
☐	8	J BONE JOINT SURG BR	0301-620X	18253	2.832	3.405	0.416	296	>10.0	0.01736	0.648
☐	9	ARTHROSCOPY	0749-8063	8684	3.024	3.079	0.616	229	6.8	0.01675	0.780
☐	10	J ARTHROPLASTY	0883-5403	7227	2.384	2.293	0.248	270	7.4	0.01615	0.722
☐	11	INJURY	0020-1383	6623	1.975	2.336	0.309	282	6.3	0.01584	0.660
☐	12	GAIT POSTURE	0966-6362	4909	2.123	2.693	0.286	245	5.5	0.01254	0.705
☐	13	KNEE SURG SPORT TR A	0942-2056	4309	2.209	2.254	0.301	339	5.0	0.01223	0.588
☐	14	J SHOULDER ELB SURG	1058-2746	5242	2.747	2.818	0.283	230	6.6	0.01207	0.798
☐	15	J HAND SURG-AM	0363-5023	7364	1.354	1.778	0.199	266	>10.0	0.01173	0.499
☐	16	BMC MUSCULOSKEL DIS	1471-2474	2444	1.577	2.324	0.172	285	3.9	0.01155	0.737
☑	17	CLIN BIOMECH	0268-0033	5009	2.071	2.468	0.244	156	7.6	0.01099	0.792
☐	18	SPINE J	1529-9430	2956	3.290		0.781	151	4.7	0.01093	
☐	19	J ORTHOP TRAUMA	0890-5339	4713	2.135	2.651	0.165	176	7.6	0.01043	0.844
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☐	3	SPINE J	1529-9430	2956	3.290		0.781	151	4.7	0.01093	
☐	4	J BONE JOINT SURG AM	0021-9355	34294	3.272	4.289	0.303	310	>10.0	0.03435	0.937
☐	5	PHYS THER	0031-9023	7427	3.113	3.517	1.053	133	>10.0	0.01019	0.884
☐	6	ARTHROSCOPY	0749-8063	8684	3.024	3.079	0.616	229	6.8	0.01675	0.780
☐	7	J ORTHOP SPORT PHYS	0190-6011	3272	3.000	2.980	0.645	93	8.5	0.00527	0.723
☐	8	J BONE JOINT SURG BR	0301-620X	18253	2.832	3.405	0.416	296	>10.0	0.01736	0.648
☐	9	J ORTHOP RES	0736-0266	10618	2.811	3.197	0.480	281	8.3	0.02115	1.007
☐	10	J SHOULDER ELB SURG	1058-2746	5242	2.747	2.818	0.283	230	6.6	0.01207	0.798
☐	11	J AM ACAD ORTHOP SUR	1067-151X	2480	2.662	2.955	0.247	89	6.2	0.00809	1.092
☐	12	CLIN ORTHOP RELAT R	0009-921X	28888	2.533	2.617	0.379	420	>10.0	0.03555	0.901
☐	13	J ARTHROPLASTY	0883-5403	7227	2.384	2.293	0.248	270	7.4	0.01615	0.722
☐	14	KNEE SURG SPORT TR A	0942-2056	4309	2.209	2.254	0.301	339	5.0	0.01223	0.588
☐	15	ACTA ORTHOP	1745-3674	6454	2.168	2.541	0.210	119	>10.0	0.01037	0.845
☐	16	J ORTHOP TRAUMA	0890-5339	4713	2.135	2.651	0.165	176	7.6	0.01043	0.844
☐	17	GAIT POSTURE	0966-6362	4909	2.123	2.693	0.286	245	5.5	0.01254	0.705
☐	18	CLIN J SPORT MED	1050-642X	2320	2.119	2.356	0.405	84	6.6	0.00543	0.689
☐	19	SPINE	0362-2436	32709	2.078	2.949	0.363	614	9.7	0.04821	0.855
☑	20	CLIN BIOMECH	0268-0033	5009	2.071	2.468	0.244	156	7.6	0.01099	0.792

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☐	1	J APPL PHYSIOL	8750-7587	39387	3.753	4.103	0.790	405	>10.0	0.05457	1.274
☐	2	MED SCI SPORT EXER	0195-9131	24428	4.431	5.017	0.741	293	9.3	0.03607	1.407
☐	3	AM J SPORT MED	0363-5465	14958	3.792	4.427	0.626	313	7.6	0.02732	1.159
☐	4	ARCH PHYS MED REHAB	0003-9993	14982	2.284	2.655	0.440	284	9.3	0.02075	0.759
☐	5	BRIT J SPORT MED	0306-3674	7592	4.144	3.790	1.104	193	5.9	0.01801	1.019
☐	6	EUR J APPL PHYSIOL	1439-6319	10139	2.147	2.321	0.433	321	8.7	0.01725	0.641
☐	7	GAIT POSTURE	0966-6362	4909	2.123	2.693	0.286	245	5.5	0.01254	0.705
☐	8	KNEE SURG SPORT TR A	0942-2056	4309	2.209	2.254	0.301	339	5.0	0.01223	0.588
☐	9	J SHOULDER ELB SURG	1058-2746	5242	2.747	2.818	0.283	230	6.6	0.01207	0.798
☑	10	CLIN BIOMECH	0268-0033	5009	2.071	2.468	0.244	156	7.6	0.01099	0.792
☐	11	J ORTHOP TRAUMA	0890-5339	4713	2.135	2.651	0.165	176	7.6	0.01043	0.844
☐	12	SPORTS MED	0112-1642	6646	5.155	5.770	0.574	61	8.7	0.01036	1.605
☐	13	J STRENGTH COND RES	1064-8011	6018	1.831	2.338	0.217	465	4.9	0.00973	0.359
☐	14	J SPORT SCI	0264-0414	4696	1.931	2.446	0.209	196	7.2	0.00877	0.616
☐	15	SCAND J MED SCI SPOR	0905-7188	3087	2.867	3.024	0.577	163	5.7	0.00775	0.849
☐	16	INT J SPORTS MED	0172-4622	5446	2.433	2.264	0.448	154	9.7	0.00770	0.545
☐	17	APPL PHYSIOL NUTR ME	1715-5312	1456	2.131	2.401	0.306	124	3.7	0.00750	0.694
☐	18	J REHABIL MED	1650-1977	2826	2.049	2.376	0.688	141	5.1	0.00726	0.645
☐	19	J ELECTROMYOGR KINES	1050-6411	2715	1.969	2.269	0.293	147	6.5	0.00613	0.604
☐	20	AM J PHYS MED REHAB	0894-9115	3334	1.581	1.848	0.281	121	8.2	0.00597	0.527

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☐	21	GAIT POSTURE	0966-6362	4909	2.123	2.693	0.286	245	5.5	0.01254	0.705
☐	22	CLIN J SPORT MED	1050-642X	2320	2.119	2.356	0.405	84	6.6	0.00543	0.689
☐	23	J AGING PHYS ACTIV	1063-8652	702	2.085	2.013	0.077	26	6.7	0.00162	0.586
☑	24	CLIN BIOMECH	0268-0033	5009	2.071	2.468	0.244	156	7.6	0.01099	0.792
☐	25	J REHABIL MED	1650-1977	2826	2.049	2.376	0.688	141	5.1	0.00726	0.645
☐	26	INT J SPORT NUTR EXE	1526-484X	1327	2.010	2.195	0.364	55	7.3	0.00230	0.530
☐	27	J ELECTROMYOGR KINES	1050-6411	2715	1.969	2.269	0.293	147	6.5	0.00613	0.604
☐	28	J SPORT SCI	0264-0414	4696	1.931	2.446	0.209	196	7.2	0.00877	0.616
☐	29	PSYCHOL SPORT EXERC	1469-0292	1200	1.867	2.590	0.444	81	4.7	0.00378	0.687
☐	30	J STRENGTH COND RES	1064-8011	6018	1.831	2.338	0.217	465	4.9	0.00973	0.359
☐	31	INT J SPORT PHYSIOL	1555-0265	438	1.796	1.972	0.167	48	3.4	0.00175	0.440
☐	31	J ATHL TRAINING	1062-6050	2278	1.796	2.935	0.214	84	6.7	0.00492	0.760
☐	33	HUM MOVEMENT SCI	0167-9457	2135	1.775	2.490	0.309	94	8.3	0.00434	0.767
☐	34	HIGH ALT MED BIOL	1527-0297	539	1.771	1.693	0.425	40	5.3	0.00127	0.418
☐	35	KNEE	0968-0160	1577	1.736	1.901	0.240	104	5.3	0.00544	0.613
☐	36	PEDIATR EXERC SCI	0899-8493	1183	1.711	2.010	0.043	47	8.7	0.00188	0.538
☐	37	J INT SOC SPORT NUTR	1550-2783	259	1.643	1.880	0.083	24	3.6	0.00086	0.402
☐	38	J MOTOR BEHAV	0022-2895	1753	1.638	1.775	0.167	54	>10.0	0.00256	0.615
☐	39	AM J PHYS MED REHAB	0894-9115	3334	1.581	1.848	0.281	121	8.2	0.00597	0.527
☐	40	CLIN SPORT MED	0278-5919	1529	1.554	1.973	0.860	57	9.7	0.00235	0.575

Curriculum Vitae

Mein Lebenslauf wird aus datenschutzrechtlichen Gründen in der elektronischen Version meiner Arbeit nicht veröffentlicht.

Complete List of Publications

(in chronological order)

Zhu, R., Zander, T., Dreischarf, M., Rohlmann, A., Duda, G. and Schmidt, H.. Considerations when loading spinal finite element model with predicted muscle forces from inverse static analyses. *(under revision, Journal of Biomechanics)*

Dreischarf, M., Rohlmann, A., **Zhu, R**., Schmidt, H. and Zander, T.. Is it possible to estimate the compressive force in the lumbar spine from intradiscal pressure measurements? *(under revision, Medical Engineer & Physics)*

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