REFERENCES

[1] A. Schiele, "Fundamentals of Ergonomic Exoskeleton Robots," *Ph.D Dissertation*, Delft University, 2008.

[2] J. C. Perry, J. Rosen, and S. Burns, "Upper-Limb Powered Exoskeleton Design," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 4, pp. 408–417, 2007.

[3] T. Nef, M. Mihelj, G. Kiefer, C. Perndl, R. Müller, and R. Riener, "ARMin – Exoskeleton for Arm Therapy in Stroke Patients," in *IEEE 10th International Conference on Rehabilitation Robotics*, 2007, vol. 00, no. c, pp. 68–74.

[4] R. A. R. C. Gopura and K. Kiguchi, "An Exoskeleton Robot for Human Forearm and Wrist Motion Assist," *Journal of Advanced Mechanical Design, Systems and Manufacturing*, vol. 2, no. 6, pp. 1067–1083, 2008.

[5] E. Cattin, S. Roccella, N. Vitiello, and M. C. Carrozza, "NEUROExos Elbow Module: A New Exoskeleton for Elbow Rehabilitation," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2011, pp. 1419–1426.

[6] C. Yang, J. Zhang, Y. Chen, Y. Dong, and Y. Zhang, "A Review of Exoskeleton-type Systems and Their Key Technologies," *Journal of Mechanical Engineering Science*, pp. 1599–1612, 2008.

[7] U. N. Population Division, DESA, "Magnitude and Speed of Population Ageing: World Population Ageing 1950-2050." [Online]. Available: www.un.org/esa/population/publications/worldageing19502050/ . [Accessed: 15-Oct-2013].

[8] A. Schiele, "Ergonomics of Exoskeletons: Subjective Performance Metrics," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009, pp. 480–485.

[9] M. Esmaeili, K. Gamage, E. Tan, and D. Campolo, "Ergonomic Considerations for Anthropomorphic Wrist Exoskeletons: A Simulation Study on the Effects of Joint Misalignment," in *IEEE/RSJ International Conference on Intellignet Robots and Systems*, 2011, pp. 4905–4910.

[10] L. Lucas, M. Dicicco, and Y. Matsuoka, "An EMG-Controlled Hand Exoskeleton for Natural Pinching," *Journal of Robotics and Mechatronics*, vol. 16, no. 5, pp. 1–7, 2004.

[11] Z. O. Khokhar, Z. G. Xiao, and C. Menon, "Surface EMG Pattern Recognition for Real-Time Control of A Wrist Exoskeleton," *BioMedical Engineering OnLine*, pp. 1–17, 2010.

[12] T. Nef, R. Riener, and M. Mihelj, "ARMin II – 7 DoF Rehabilitation Robot: Mechanics and Kinematics," in *IEEE Internatational Conference on Robotics and Automation*, 2007, pp. 4120–4125.

[13] Z. Song and S. Guo, "Design Process of Exoskeleton Rehabilitation Device and Implementation of Bilateral Upper Limb Motor Movement," *Journal of Medical and Biological Engineering*, vol. 32, no. 5, pp. 323–330, 2011.

[14] T. Lenzi, N. Vitiello, S. Roccella, F. Vecchi, M. C. Carrozza, S. M. De Rossi, and M. Chiara, "NEUROExos: A Variable Impedance Powered Elbow Exoskeleton," in *IEEE International Conference on Robotics and Automation*, 2011, pp. 1419–1426.

[15] E. Rocon, J. M. Belda-Lois, A. F. Ruiz, M. Manto, J. C. Moreno, and J. L. Pons, "Design and Validation of a Rehabilitation Robotic Exoskeleton for Tremor Assessment and Suppression," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 367–378, 2007.

[16] R. A. R. C. Gopura, K. Kiguchi, and Y. Li, "SUEFUL-7: A 7DOF Upper-Limb Exoskeleton Robot with Muscle-Model-Oriented EMG-Based Control," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009, pp. 1126–1131.

[17] H. Kim, Z. Li, D. Milutinovi, and J. Rosen, "Resolving the Redundancy of a Seven DOF Wearable Robotic System Based on Kinematic and Dynamic Constraint," in *IEEE International Conference on Robotics and Automation*, 2012, pp. 305–310.

[18] S. Moubarak, M. T. Pham, T. Pajdla, and T. Redarce, "Design and Modeling of an Upper Extremity Exoskeleton," in *International Congress of the IUPSEM: Medical and Physical Biomedical Engineering World*, 2009, pp. 476–479.

[19] M. K. O. Malley, A. Gupta, V. Patoglu, and C. Burgar, "Design , Control and Performance of RiceWrist: A Force Feedback Wrist Exoskeleton for Rehabilitation and Training," *International Journal of Robotics Research*, vol. 27, no. 2, pp. 233–251, 2008.

[20] S. S. Fusion, K. Kiguchi, S. Kariya, K. Watanabe, and K. Izumi, "An Exoskeletal Robot for Human Elbow Motion," *IEEE Transactions on Systems, Man and Cybernrtics*, vol. 31, no. 3, pp. 353–361, 2001.

[21] D. S. Andreasen, S. K. Allen, and D. . Backus, "Exoskeleton with EMG Based Active Assistance for Rehabilitation," in *IEEE 9th International Conference on Rehabilitation Robotics*, 2005, pp. 333–336.

[22] J. L. Pons, E. Rocon, A. F. Ruiz, and J. C. Moreno, "Upper-Limb Robotic Rehabilitation Exoskeleton: Tremor Suppression," in *Rehabilitation Robots*, S. S. Kommu, Ed. Vienna, Austria: InTech, 2007, pp. 453–469.

[23] A. Schiele and F. C. T. Van Der Helm, "Kinematic Design to Improve Ergonomics in Human Machine Interaction," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 14, no. 4, pp. 456–469, 2006.

[24] M. Mihelj, "Human Arm Kinematics for Robot Based Rehabilitation," *Robotica*, vol. 24, no. 03, pp. 377–383, 2006.

[25] O. Khatib and B. Siciliano, Eds., *Springer Handbook of Robotics*. Springer, 2008.

[26] H. Kim, L. M. Miller, N. Byl, G. M. Abrams, and J. Rosen, "Redundancy Resolution of the Human Arm and an Upper Limb Exoskeleton," *IEEE Transactions on Biomedical Engineering*, vol. 59, no. 6, pp. 1770–1779, 2012.

[27] W. Khalil and E. Dombre, *Robot Manipulators, Modeling, Performance Analysis and Control*, 1st ed. ISTE Ltd, 2007.

[28] H. Kim, L. M. Miller, A. Al-refai, M. Brand, and J. Rosen, "Redundancy Resolution of a Human Arm for Controlling a Seven DOF wearable Robotic System," in *IEEE EMBS 33rd Annual International Conference*, 2011, pp. 3471–3474.

[29] S. J. Ball, I. E. Brown, and S. H. Scott, "A Planar 3DOF Robotic Exoskeleton for Rehabilitation and Assessment," in *29th Annual International Conference of the IEEE EMBS*, 2007, pp. 4024–4027.

[30] T. Yoshikawa, "Manipulability of Robotic Mechanisms," *The International Journal of Robotic Research*, vol. 4, no. 3, pp. 2–9, 1985.

[31] B. Siciliano, "Kinematic Control of Redundant Robot Manipulators: A Tutorial," *Journal of Intelligent and Robotic Systems*, vol. 3, no. 5, pp. 201–212, 1990.

[32] B. Siciliano, S. Lorenzo, V. Luigi, and O. Giuseppe, *Robotics, Modeling, Planning and Control*, 1st ed. Springer, 2009, pp. 150–159.

[33] J. F. Veneman, R. Kruidhof, E. E. G. Hekman, R. Ekkelenkamp, and E. H. F. Van Asseldonk, "Design and Evaluation of the LOPES Exoskeleton Robot for

Interactive Gait Rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 15, no. 3, pp. 379–386, 2007.

[34] L. Zollo, B. Siciliano, A. De Luca, E. Guglielmelli, and P. Dario, "Compliance Control for an Anthropomorphic Robot with Elastic Joints : Theory and Experiments," *Journal of Dynamics Systems, Measurement and Control*, vol. 127, no. 4, pp. 321–328, 2005.

[35] S. Drive, "Stock drive products/Sterling instruments." [Online]. Available: http://www.sdp-si.com/. [Accessed: 10-May-2013].

[36] L. L. Pons, Ed., *Wearable Robots, Biomechatronic Exoskeletons*, 1st ed. John Wiley & Sons, Ltd, 2008.

[37] S. J. Ball, I. E. Brown, and S. H. Scott, "MEDARM: A Rehabilitation Robot with 5DOF at the Shoulder Complex," in *IEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2007, pp. 25–30.

[38] A. Frisoli, M. Bergamasco, L. Borelli, A. Montagner, G. Greco, C. Procopio, M. C. Carboncini, and B. Rossi, "Robotic Assisted Rehabilitation in Virtual Reality with the L-EXOS," in *7th ICDVRAT with ArtAbilitation*, 2008, pp. 253–260.

[39] M. Mistry, P. Mohajerian, and S. Schaal, "An Exoskeleton Robot for Human Arm Movement Study," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005, pp. 4071–4076.

[40] K. Kiguchi, M. H. Rahman, M. Sasaki, and K. Teramoto, "Development of a 3DOF Mobile Exoskeleton Robot for Human Upper-Limb Motion Assist," *Robotics and Autonomous Systems*, vol. 56, no. 8, pp. 678–691, 2008.

[41] N. G. Tsagarakis and D. G. Caldwell, "Development and Control of a ' Soft-Actuated ' Exoskeleton for Use in Physiotherapy and Training," *Journal of Autonomous Robots*, vol. 15, pp. 21–33, 2003.

[42] F. Rocchi, A. Frisoli, A. Dettori, F. Salsedo, and M. Bergamasco, "A New Force-Feedback Arm Exoskeleton for Haptic Interaction in Virtual Environments," in *First Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2005, pp. 195–201.

[43] C. Carignan and M. Liszka, "Design of an Arm Exoskeleton with Scapula Motion for Shoulder Rehabilitation," in *International Conference on Advanced Robotics*, 2005, pp. 524–531.

[44] W. Chou, T. Wang, and J. Xiao, "Haptic Interaction with Vitual Environment Using an Arm Type Exoskeleton Device," in *IEEE Internatational Conference on Robotics and Automation*, 2004, pp. 1992–1997.

[45] E. Rocon, A. F. Ruiz, J. L. Pons, J. . Belda-Lois, and J. J. . Lacuesta, "Rehabilitation Robotics: A Wearable Exo-Skeleton for Tremor Assessment and Suppression," in *IEEE International Conference on Robotics and Automation*, 2005, pp. 2283–2288.

[46] R. A. R. C. Gopura, "Development and Control of Upper-Limb Exoskeleton Robots," Saga University, Japan, 2009.

[47] D. Naidu, C. Cunniffe, R. Stopforth, G. Bright, and S. Davrajh, "Upper and Lower Exoskeleton Limbs for Assistive and Rehabilitative Applications," in *4th Robotics and Mechatronics Conference of South Africa (ROBMECH 2011)*, 2011, pp. 23–25.

[48] T. Noritsugu, H. Yamamoto, D. Sasaki, and M. Takaiwa, "Wearable Power Assist Device for Hand Grasping Using Pneumatic Artificial Rubber Muscle," in *SICE Annual Conference*, 2004, pp. 420–426.

[49] D. Thompson, "Wrist Joint Complex," 2011. [Online]. Available: www.moon.ouhsc.edu/dthompso/namics/wrist.htm#move. [Accessed: 27-Jan-2014].

[50] J. A. Craig, "Morphopedics," *Wiki dot*, 2012. [Online]. Available: http://morphopedics.wikidot.com/physical-therapy-management-of-colles-fracture. [Accessed: 10-Sep-2013].

[51] R. A. R. C. Gopura and K. Kiguchi, "Mechanical Designs of Active Upper-Limb Exoskeleton Robots: State-of-the-Art and Design-Difficuties," in *IEEE 11th International Conference on Rehabilitation Robotics*, 2009, pp. 178–187.

[52] Y. Youm and A. Flatt, "Design of a Total Wrist Prosthesis," *Annals of Biomedical Engineering*, vol. 12, pp. 247–262, 1984.

[53] J. J. C. and S. W. W. C. P. Neu, "'In Vivo Kinematic Behavior of the Radio-Capitate Joint during Wrist Flexion-Extension and Radio-Ulnar Deviation,' *J. Biomech.*, vol. 34, pp. 1429–1438, 2001.

[54] R. A. Loredo, D. G. Sorge, and G. Garcia, "Radiographic Evaluation of the Wrist: A Vanishing Art," *Elsevier:Roentgenology*, pp. 248–289, 2005.

[55] M. F. Chan, D. R. Giddings, C. S. Chandler, C. Crags, R. D. Plant, and M. C. Day, "An Experimentally Confirmed Statistical Model on Arm Movement," *Human Movement Science*, vol. 22, no. 02, pp. 631–648, 2004.

[56] J. Rosen, J. C. Perry, N. Manning, S. Burns, and B. Hannaford, "The Human Arm Kinematics and Dynamics During Daily Activities – Toward a 7 DOF Upper Limb Powered Exoskeleton," in *12th International Conference on Advanced Robotics- ICAR*, 2005, pp. 24–32.

[57] J. Yang, K. A. Malek, and K. Nebel, "Reach Envelop of A 9-Degree of Freedom Model of The Upper Extremity," *International Journal of Robotics and Automation*, vol. 20, no. 4, pp. 240–259, 2005.

[58] G. Morel and N. Jarrasse, "Connecting a Human Limb to an Exoskeleton," *IEEE Transactions on Robotics*, vol. 28, no. 3, pp. 697–709, 2012.

[59] J. J. Craig, *Introduction to Robotics, Mechanics and Control*, 3rd ed. Pearson Prentice Hall, 2005.

[60] K. Abdel-malek, H. J. Yeh, and S. Othman, "Interior and Exterior Boundaries to the Workspace of Mechanical Manipulators," *Robotics and Computer Integrated Manufacturing*, vol. 16, pp. 365–376, 2000.

[61] E. Mattar, "A Survey of Bio-Inspired Robotics Hands Implementation : New directions in Dexterous Manipulation," *Robotics and Autonomous Systems*, vol. 61, no. 5, pp. 517–544, 2013.

[62] A. Gupta and M. K. O. Malley, "Design of a Haptic Arm Exoskeleton for Training and Rehabilitation," *IEEE/ASME Transactions on Mechatronics*, vol. 11, no. 3, pp. 280–289, 2006.

[63] K. Kiguchi and Y. Hayashi, "An EMG-Based Control for an Upper-Limb Power-Assist Exoskeleton Robot," *IEEE Transactions on Systems, Man and Cybernrtics*, vol. 42, no. 4, pp. 1064–1071, 2012.

[64] K. Kong and M. Tomizuka, "Control of Exoskeletons Inspired by Fictitious Gain in Human Model," *IEEE/ASME Transactions on Mechatronics*, vol. 14, no. 6, pp. 689–698, 2009.

[65] W. Huo, J. Huang, Y. Wang, J. Wu, and L. Cheng, "Control of Upper-Limb Power-Assist Exoskeleton Based on Motion Intention Recognition," in *IEEE International Conference on Robotics and Automation*, 2011, pp. 2243–2248.

[66] P. Martin and M. R. Emami, "Neuro-fuzzy Compliance Control for Rehabilitation Robotics," in *3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2010, pp. 560–565.

[67] M. . Oskoei and H. Hu, "Support Vector Machine-Based Classification Scheme for Myoelectric Control Applied to Upper Limb," *IEEE Transactions on Biomedical Engineering*, vol. 55, no. 8, pp. 1956–1965, 2008.

[68] S. Paul, H. Kim, Z. Li, D. Milutinovi, and J. Rosen, “Resolving the Redundancy of a Seven DOF Wearable Robotic System Based on Kinematic and Dynamic Constraint,” in *IEEE International Conference on Robotics and Automation*, 2012, pp. 305–310.

[69] J. Rosen and J. C. Perry, “Upper Limb Powered Exoskeleton,” *International Journal of Humanoid Robotics*, vol. 4, no. 3, pp. 529–548, 2007.

[70] S. B. Kesner, L. Jentoft, F. L. Hammond, R. D. Howe, and M. Popovic, “Design Considerations for an Active Soft Orthotic System for Shoulder Rehabilitation,” in *IEEE/EMBC Annual International Conference*, 2011, pp. 8130–8134.

[71] E. Wolbrecht, D. Reinkensmeyer, and J. Bobrow, “Pneumatic Control of Robots for Rehabilitation,” *The International Journal of Robotics Research*, vol. 29, no. 1, pp. 23–38, 2010.

[72] J. He, E. J. Koeneman, R. S. Schultz, H. Huang, J. Wanberg, D. E. Herring, T. Sugar, and J. B. Koeneman, “Design of a Robotic Upper Extremity Repetitive Therapy Device,” in *9th IEEE International Conference on Rehabilitation Robotics*, 2005, pp. 95–98.

[73] M. H. Rahman, T. K. Ouimet, M. Saad, J. P. Kenne, and P. S. Archambault, “Development of a 4 DoFs Exoskeleton Robot for Passive Arm Movement Assistance,” *International Journal of Mechatronics and Automation*, vol. 2, no. 1, pp. 34–50, 2012.

[74] K. Nagai, I. Nakanishi, H. Hanafusa, S. Kawamura, M. Makikawa, and N. Tejima, “Development of an 8 DOF Robotic Orthosis for Assisting Human Upper Limb Motion,” in *IEEE International Conference on Robotics and Automation*, 1998, pp. 3486–3491.

[75] J. Duchêne and J. Hogrel, “A Model of EMG Generation,” *IEEE Transactions on Biomedical Engineering*, vol. 47, no. 2, pp. 192–201, 2000.

[76] A. Merlo, D. Farina, and R. Merletti, “Detection From Surface EMG Signals,” *IEEE Transactions on Biomedical Engineering*, vol. 50, no. 3, pp. 316–323, 2003.

[77] R. A. R. C. Gopura and K. Kiguchi, “Application of Surface Electromyographic Signals to Control Exoskeleton Robots,” in *Applications of EMG in Clinical and Sports Medicine*, Vienna, Austria: InTech, 2007, pp. 69–94.

[78] K. Kiguchi, Y. Kose, and Y. Hayashi, “An Upper-Limb Power-Assist Exoskeleton Robot With Task-Oriented Perception-Assist,” in *3rd IEEE RAS*

& EMBS International Conference on Biomedical Robotics and Biomechatronics, 2010, pp. 88–93.

[79] P. Konrad, “ABC of EMG: A Practical Introduction to Kinesiological Electromyography,” Naraxon Inc, USA, 2005.

[80] T. Lenzi, S. Marco, M. De Rossi, N. Vitiello, and M. C. Carrozza, “Intention-Based EMG Control for Powered Exoskeletons,” *IEEE Transactions on Biomedical Engineering*, vol. 59, no. 8, pp. 2180–2190, 2012.

[81] N. Jarrassé, M. Tagliabue, J. V. G. Robertson, A. Maiza, V. Crocher, A. Roby-Brami, and G. Morel, “A Methodology to Quantify Alterations in Human Upper Limb Movement During Co-Manipulation With an Exoskeleton,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 4, pp. 389–397, 2010.

[82] K. Kong and D. Jeon, “Fuzzy Control of a New Tendon-Driven Exoskeletal Power Assistive Device,” in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2005, pp. 146–151.

[83] L. M. Miller and J. Rosen, “Comparison of Multi-Sensor Admittance Control in Joint Space and Task Space for a Seven Degree of Freedom Upper Limb Exoskeleton,” in *3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, 2010, pp. 70–75.

[84] W. Yu and J. Rosen, “A Novel Linear PID Controller for an Upper Limb Exoskeleton,” in *49th IEEE Conference on Decision and Control*, 2010, pp. 3548–3553.

[85] J. M. P. Gunasekara, R. A. R. C. Gopura, T. S. S. Jayawardane, and S. W. H. M. T. D. Lalitharathne, “Control Methodologies for Upper Limb Exoskeleton Robots,” in *IEEE/SICE International Symposium on System Intergration*, 2012, pp. 19–24.

[86] K. Kiguchi, M. Liyanage, and K. Kosel, “Perception Assist with Active Camera for an Upper-Limb Power-Assist Exoskeleton,” in *Asia International Symposium on Mechatronics*, 2008, pp. 387–392.

[87] P. H. Chang, “A Dexterity Measure for the Kinematic Control of Robot Manipualtor with Redundancy,” Artificail Intelligence Laboratory, MIT, 1988.

[88] J. Kimt and P. K. Khoslas, “Dexterity Measures for Design and Control of Manipulators,” in *IEEE/RSJ International Workshop on Intelligent Robots and Systems*, 1991, pp. 758–763.

[89] R. M. Murray, Z. Li, and S. Sastry, *A Mathematical Introduction to Robotic Manipulation*, 1st ed. CRC Press, 1994.

[90] S. Kucuk and Z. Bingul, "Robot Workspace Optimization Based on a Novel Local and Global Performance Indices," in *IEEE International Symposium on Industrial Electronics*, 2005, pp. 1593–1598.

[91] T. Tanev and B. Stoyanov, "On the Performance Indexes for Robot Manipulators," *Problems of Engineering Cybernetics and Robotics*, vol. 49, pp. 64–71, 2000.

[92] S. Kucuk and Z. Bingul, "Comparative Study of Performance Indices for Fundamental Robot Manipulators," *Robotics and Automation systems*, vol. 54, pp. 567–573, 2006.

[93] S. H. H. Zargarbashi, W. Khan, and J. Angeles, "The Jacobian Condition Number as a Dexterity Index in 6R Machining Robots," *Journal of Robotics and Computer Integrated Manufacturing*, vol. 28, no. 6, pp. 694–699, 2012.

[94] B. Tondu, "A Theorem on the Manipulability of Redundant Serial Kinematic Chains," Electrical Engineering Dept. Campus de Rangueil, France, 2007.

[95] A. A. Maciejewski and C. A. Klein, "Obstacle Avoidance for Kinematically Redundant Manipulators in Dynamically Varying Environments," *The International Journal of Robotics Research*, vol. 4, no. 3, pp. 109–116, 1985.

[96] H. Abdi and S. Nahavandi, "Well-Conditioned Configurations of Fault-Tolerant Manipulators," *Journal of Robotics and Autonomous Systems*, vol. 60, no. 2, pp. 242–251, 2009.

[97] Y. Gan and X. Dai, "Human-like Manipulation Planning for Articulated Manipulator," *Journal of Bionic Engineering*, vol. 9, no. 4, pp. 434–445, 2012.

[98] A. Gupta and M. K. O. Malley, "Robotic Exoskeletons for Upper Extremity Rehabilitation," in *Rehabilitation Robotics*, S. S. Kommu, Ed. Vienna, Austria: InTech, 2007, pp. 371–396.

[99] D. Prattichizzo, M. Malvezzi, M. Gabiccini, and A. Bicchi, "On the Manipulability Ellipsoids of Underactuated Robotic Hands with Compliance," *Journal of Robotics and Autonomous Systems*, vol. 60, no. 3, pp. 337–346, 2011.

[100] I. Mansouri and M. Ouali, "The Power Manipulability – A New Homogeneous Performance Index of Robot Manipulators," *Robotics and Computer Integrated Manufacturing*, vol. 27, no. 2, pp. 434–449, 2011.

[101] S. Yahya, M. Moghavvemi, and H. A. F. Mohamed, "Singularity Avoidance of a Six Degree of Freedom Three Dimensional Redundant Planar

Manipulator," *Journal of Computers and Mathematics with Applications*, vol. 64, no. 5, pp. 856–868, 2012.

[102] D. Oetomo and M. H. A. Ang, "Singularity Robust Algorithm in Serial Manipulators," *Journal of Robotics and Computer-Integrated Manufacturing*, vol. 25, pp. 122–134, 2009.

[103] M. Mohammed, A. Elkady, and T. Sobh, "A New Algorithm for Measuring and Optimizing the Manipulability Index," *International Journal of Advanced Robotic Systems*, vol. 6, no. 2, pp. 145–150, 2009.

[104] R. Kurazume and T. Hasegawa, "A New Index of Serial Link Manipulator Performance Combining Dynamic Manipulability and Manipulating Force Ellisoids," *IEEE Transactions on Robotics*, vol. 1, no. 8, pp. 1–8, 2002.

[105] S. Siddiqui and R. Roberts, "An Example of a Fault Tolerant Wrist Design," in *Florida Conference on Recent Advanced in Robotics*, 2012, pp. 1–4.

[106] Y. Li and Q. Xu, "Kinematic Analysis and Design of a New 3-DOF Translational Parallel Manipulator," *Journal of Mechanical Design*, vol. 128, pp. 729–737, 2006.

[107] K. M. Ben-gharbia, A. A. Maciejewski, and R. G. Roberts, "An Illustration of Generating Robts from Optimal Fault-Tolerant Jacobians," in *International Conference on Robotics and Applications*, 2010, pp. 453–460.

[108] J. C. Perry, J. M. Powell, and J. Rosen, "Isotropy of an Upper Limb Exoskeleton and the Kinematics and Dynamics of the Human Arm," *Applied Bionics and Biomechanics*, vol. 6, no. 2, pp. 175–191, 2009.

[109] W. Khalil and E. Dombre, *Modeling, Identification and Control of Robots*, 1st ed. Kogan Page Science, 2004.

[110] J. Klein, S. Spencer, J. Allington, J. E. Bobrow, and D. J. Reinkensmeyer, "Optimization of a Parallel Shoulder Mechanism to Achieve a High-Force, Low -Mass, Robotic-Arm Exoskeleton," *IEEE Transactions on Robotics*, vol. 26, no. 4, pp. 710–715, 2010.

[111] Y. Mao and S. K. Agrawal, "Design of a Cable-Driven Arm Exoskeleton (CAREX) for Neural Rehabilitation," *IEEE Transactions on Robotics*, vol. 28, no. 4, pp. 922–931, 2012.

[112] W. Ye, C. Yang, and Q. Xie, "The Development of an Exoskeleton Robot for Co-Manipulation of Human Upper Limb Movement," in *10th World Congress on Intelligent Control and Automation*, 2012, pp. 3909–3914.

[113] H. S. Woo and O. Kwon, "Combined Kinematic Analysis of a Hybrid 7-DOF Rehabilitation Robot," in *12th International Conference on Control, Automation and Systmes*, 2012, pp. 1752–1755.

[114] N. Ahamed, K. Sundaraj, B. Ahmad, and S. Nadarajah, "Recent Survey of Automated Rehabilitation Systems Using EMG Biosensors," *Journal of Physcological Theraphy Science*, vol. 23, no. 6, pp. 945–948, 2011.

[115] D. S. V Bandara, R. A. R. C. Gopura, K. T. M. U. Hemapala, and K. Kiguchi, "Upper Extremity Prosthetics: Current Status , Challenges and Future Directions," in *17th International Symposium on Artificial Life and Robotics (AROB)*, 2012, vol. 2012, pp. 875–880.

[116] K. Anam and A. A. Al-jumaily, "Active Exoskeleton Control Systems: State of the Art," in *International Symposium on Robotics and Intelligent Sensors (IRIS)*, 2012, vol. 41, pp. 988–994.

[117] J. Karner, W. Reichenfelser, and M. Gfoehler, "Kinematic and Kinetic Analysis of Human Motion as Design Input for an Upper Extremity Bracing System," in *International Confeence Biomedical Engineering (BioMed)*, 2012, pp. 376–383.

[118] J. P. Giuffrida, A. Lerner, R. Steiner, and J. Daly, "Upper-Extremity Stroke Therapy Task Discrimination Using Motion Sensors and Electromyography," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 16, no. 1, pp. 82–90, 2008.

[119] A. Pervez and J. Ryu, "Safe Physical Human Robot Interaction – Past , Present and Future," *Journal of Mechanical Science and Technology*, vol. 22, pp. 469–483, 2008.

[120] M. Cempini, S. M. M. De Rossi, T. Lenzi, N. Vitiello, and M. C. Carrozza, "Self-Alignment Mechanisms for Assistive Wearable Robots: A Kinetostatic Compatibility Method," *IEEE Transactions on Robotics*, vol. 29, no. 1, pp. 236–250, 2013.

[121] R. A. R. C. Gopura, D. S. V Bandara, J. M. P. Gunasekara, and T. S. S. Jayawardane, "Recent Trends in EMG-Based Control Methods for Assistive Robots," in *Electrodiagnosis in New Frontiers of Clinical Research*, 01 ed., H. Turker, Ed. InTech, 2013, pp. 237–268.

[122] J. Hammel, K. Hall, D. Lees, L. Leifer, M. Van der Loos, I. Perkash, and R. Crigler, "Clinical Evaluation of a Desktop Robotic Assistant," *Journal of Rehabilitation Research and Development*, vol. 26, no. 14, pp. 1–16, 1989.

[123] I. Kawabuchi, “A Designing of Humanoid Robot Hands in Endo skeleton and Exoskeleton Styles,” in *Humanoid Robots, New Developments*, C. de P. Filho, Ed. InTech, 2007, pp. 401–426.

[124] M. Spong, S. Hutchinson, and M. Vidyasagar, *Robot Dynamics and Control*, 1st ed. John Wiley & Sons, Ltd, 2006.

[125] P. Corke, *Robtics, Vision and Control*, 1st ed. Springer, 2011.

[126] D. J. Magermans, E. K. J. Chadwick, H. E. J. Veeger, and F. C. T. Helm, “Requirements for Upper Extremity Motions during Activities of Daily Living,” *Journal of Clinical Biomechanics*, vol. 20, no. 5, pp. 591–599, 2005.

[127] J. M. P. Gunasekara, R. A. R. C. Gopura, T. S. S. Jayawardane, and G. K. I. Mann, “Dexterity Measure of Upper Limb Exoskeleton with Improved Redundancy,” in *8th IEEE International Conference on Industrial and Information Systems*, 2013, pp. 548–553.

[128] Paredis, P. Khosla, and J. J. Christiaan, “Kinematic Design of Serial Link Manipulators from Task Specifications.” Institute for Software Research, Carnegie Mellon University, pp. 1–25, 1993.

[129] V. Fohanno, P. Lacouture, and F. Colloud, “Improvement of Upper Extremity Kinematics Estimation using a Subject-Specific Forearm Model Implemented in a Kinematic Chain,” *Journal of Biomechanics*, vol. 46, no. 6, pp. 1053–1059, 2013.

[130] A. Naaji, “Working Space Representation for the Human Upper Limb in Motion,” in *7th International Conference on Applied Computer and Applied Computational Science (ACACOS)*, 2008, pp. 394–399.

[131] J. Yang, T. Sinokrot, and K. Abdel-malek, “A General Analytic Approach for Santos Upper Extremity Workspace,” *Journal of Computers and Industrial Engineering*, vol. 54, no. 5, pp. 242–258, 2008.

[132] D. Mavrikios, V. Karabatsou, K. Alexopoulos, M. Pappas, P. Gogos, and G. Chryssolouris, “An Approach to Human Motion Analysis and Modelling,” *International Journal of Industrial Ergonomics*, vol. 36, no. 6, pp. 979–989, 2006.

[133] J. Yang and K. Abdel-Malek, “Human Reach Envelope and Zone Differentiation for Ergonomic Design,” *Journal of Human Factors and Ergonomics in Manuacturing*, vol. 19, no. 1, pp. 15–34, 2009.

[134] A. Buryanov and V. Kotiuk, “Proportions of Hand Segments,” *International Journal of Morphol*, vol. 28, no. 3, pp. 755–758, 2010.

[135] L. Leonard, D. Sirkett, G. Mullineux, G. Giddins, and A. Miles, “Development of an In-Vivo method of Wrist Joint Motion Analysis,” *Journal of Clinical Biomechanics*, vol. 20, no. 2, pp. 166–171, 2005.

[136] G. Elert, “Body Proportions,” 2006. [Online]. Available: http://hypertextbook.com/facts/2006/bodyproportions/data.xls. [Accessed: 14-Nov-2013].

PUBLICATIONS

1. **J. M. P. Gunasekara**, R. A. R. C. Gopura, T. S. S. Jayawardane, and S. W. H. M. T. D. Lalitharathne, "Control Methodologies for Upper Limb Exoskeleton Robots," in *IEEE/SICE International Symposium on System Intergration*, 2012, pp. 19–24.

2. R. A. R. C. Gopura, D. S. V Bandara, **J. M. P. Gunasekara**, and T. S. S. Jayawardane, "Recent Trends in EMG-Based Control Methods for Assistive Robots," in *Electrodiagnosis in New Frontiers of Clinical Research*, 01 ed., H. Turker, Ed. InTech, 2013, pp. 237–268.

3. **J. M. P. Gunasekara**, R. A. R. C. Gopura, T. S. S. Jayawardane, and G. K. I. Mann, "Dexterity Measure of Upper Limb Exoskeleton with Improved Redundancy," in *8th IEEE International Conference on Industrial and Information Systems*, 2013, pp. 548–553.

4. **J. M. P. Gunasekara**, R. A. R. C. Gopura, and T. S. S. Jayawardane, "A Qualitative Performance Measure for Upper Limb Exoskeleton based on Lock Joint Failures at Minimum Manipulation," in *iPURSE,* vol 18, pp.142, 2014.

5. **J.M.P Gunasekara**, R.A.R.C Gopura and T.S.S Jayawardena, "6-REXOS: Upper limb exoskeleton robot with improved pHRI", in *International journal of advanced robotic systems* (submitted for review)

<u>APPENDIX A</u>

Engineering Drawings of 6-REXOS

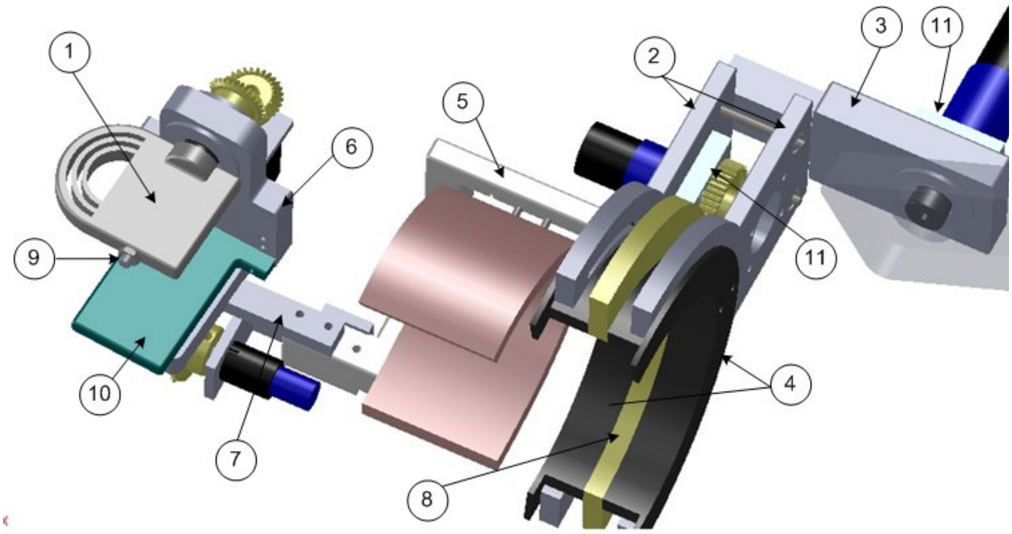
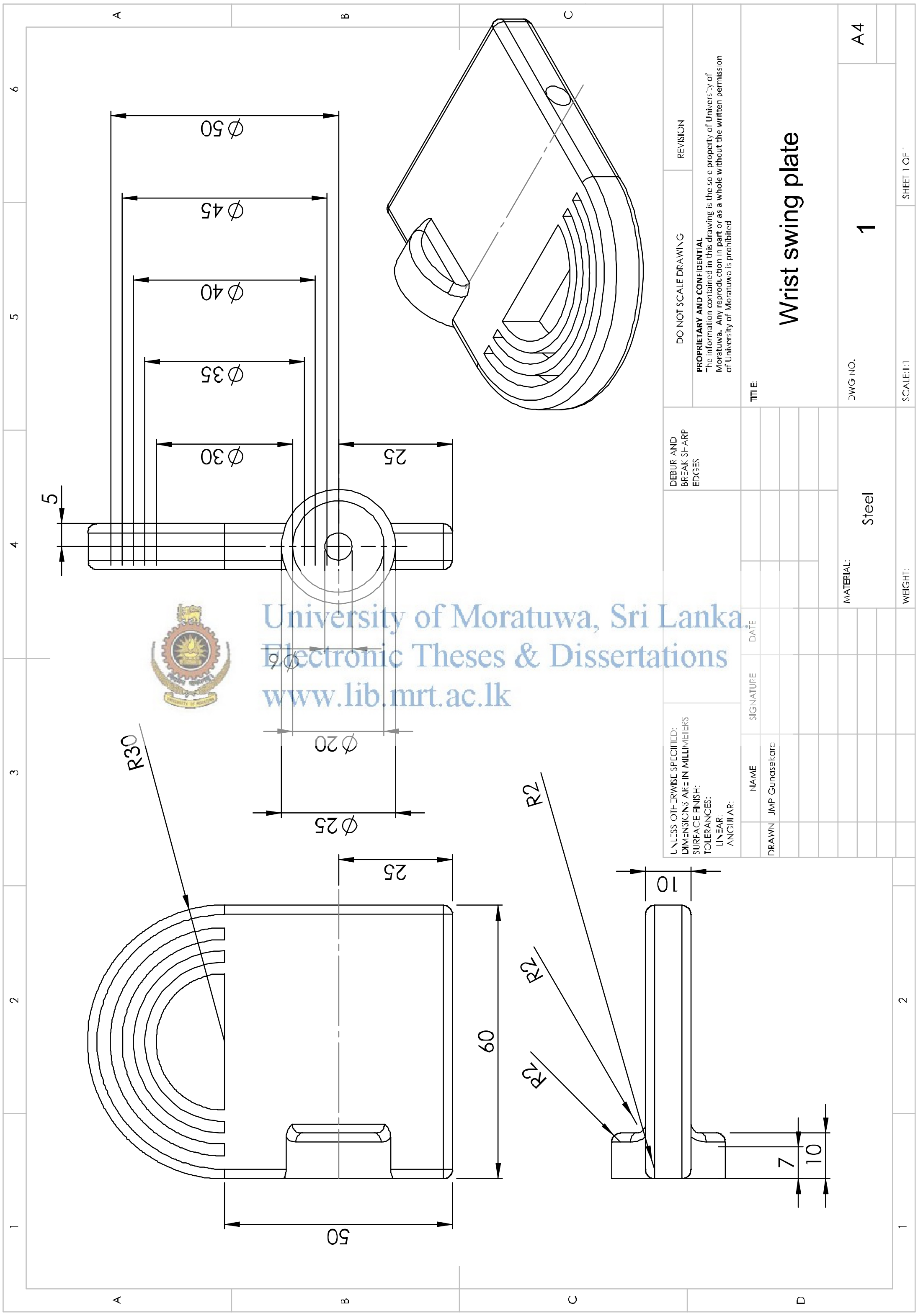


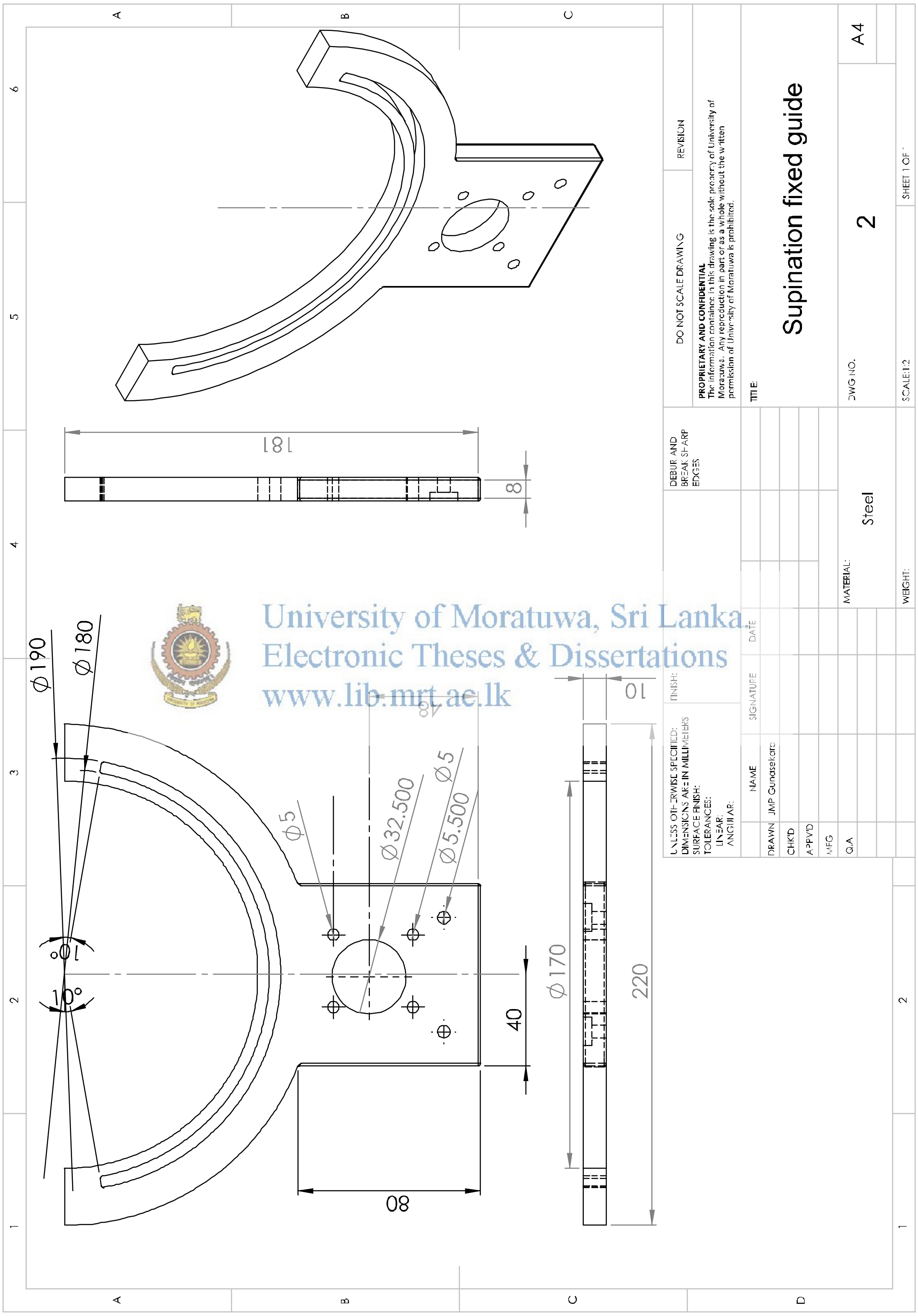
Figure A-1: Components of 6-REXOS

Table A-1: Description of components used in 6-REXOS

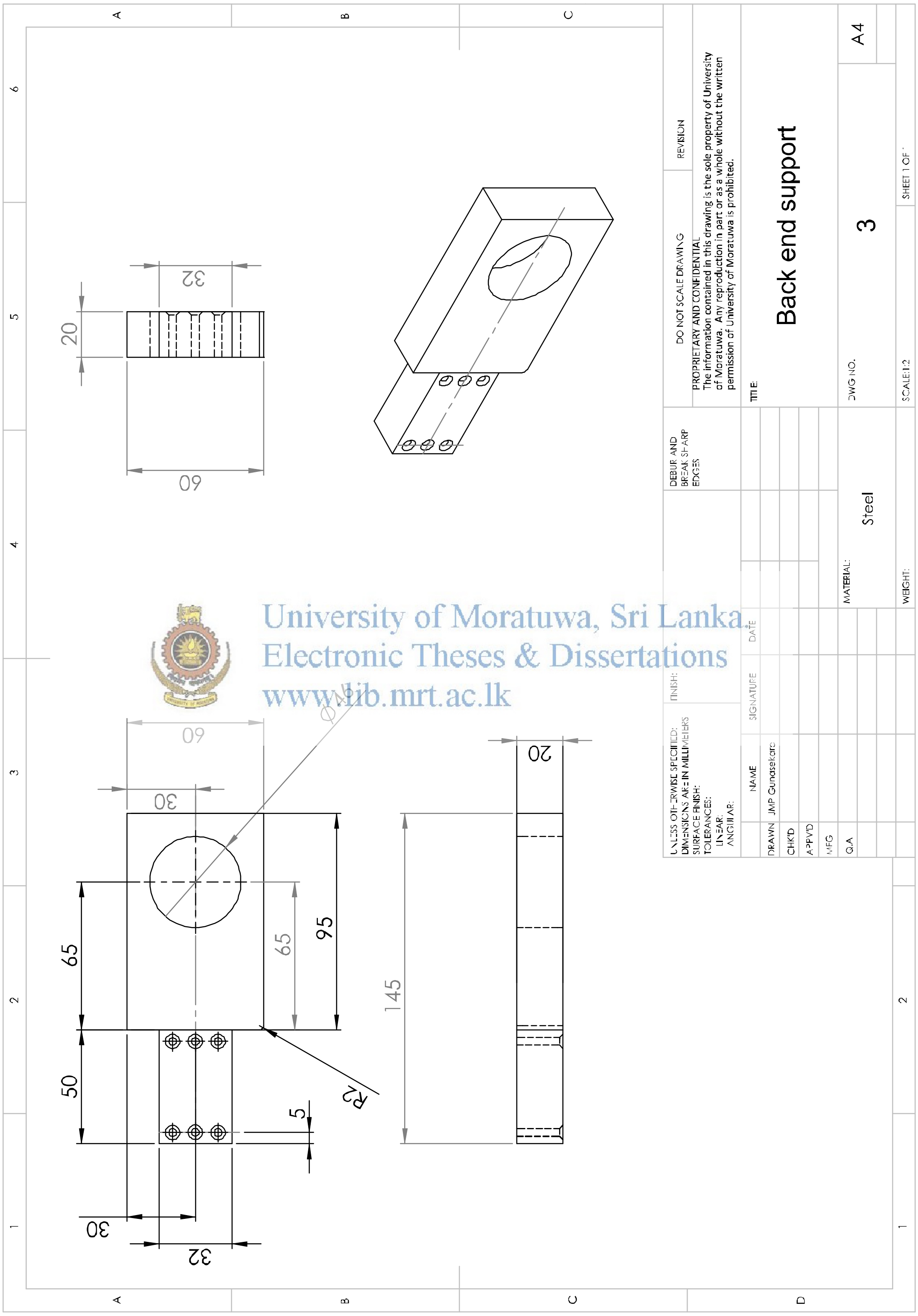
Item	Component
1	Wrist swing plate
2	Supination fixed guide
3	Back end support
4	Circular sliding plate
5	L-shape connecting link
6	Wrist L-shape part
7	Ulnar-radial bottom link
8	Forearm custom spur gear
9	Bolt-wrist top plate
10	Wrist bottom arm rest
11	Motor support plate

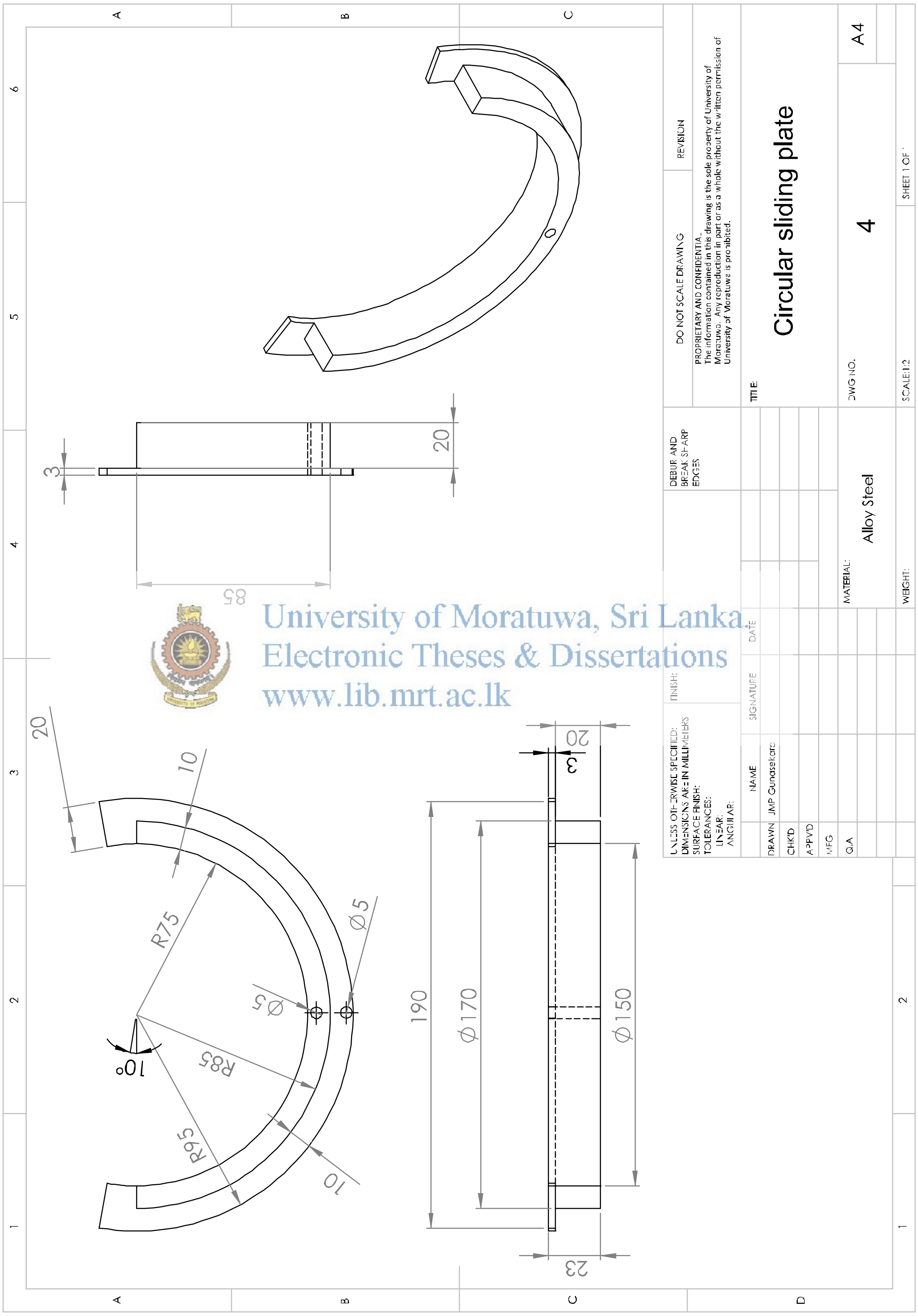


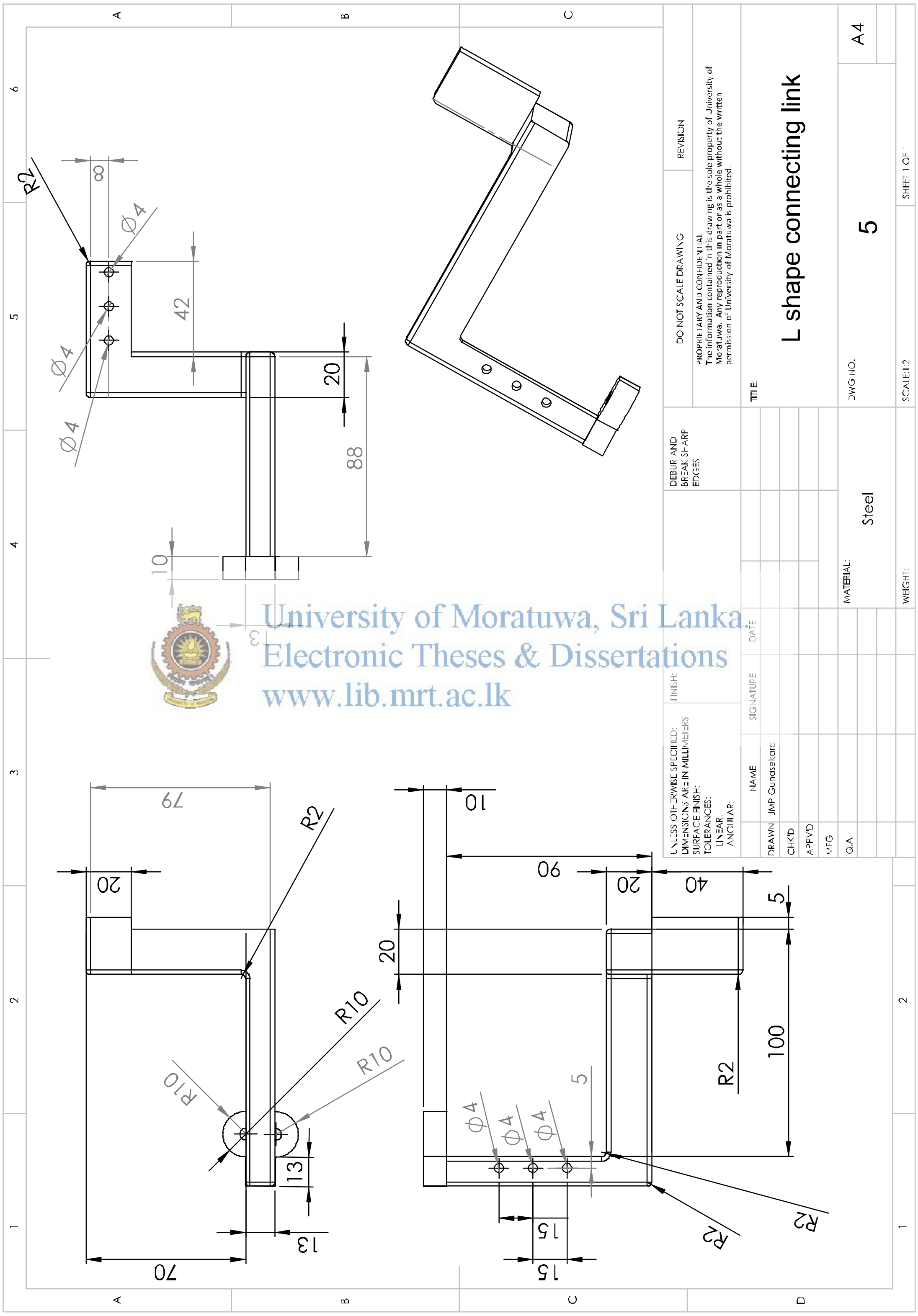
Wrist swing plate
DWG NO. 1
A4
MATERIAL: Steel
DO NOT SCALE DRAWING
REVISION
DEBUR AND BREAK SHARP EDGES
DRAWN JMP Gunasekara
SCALE:1:1
SHEET 1 OF 1

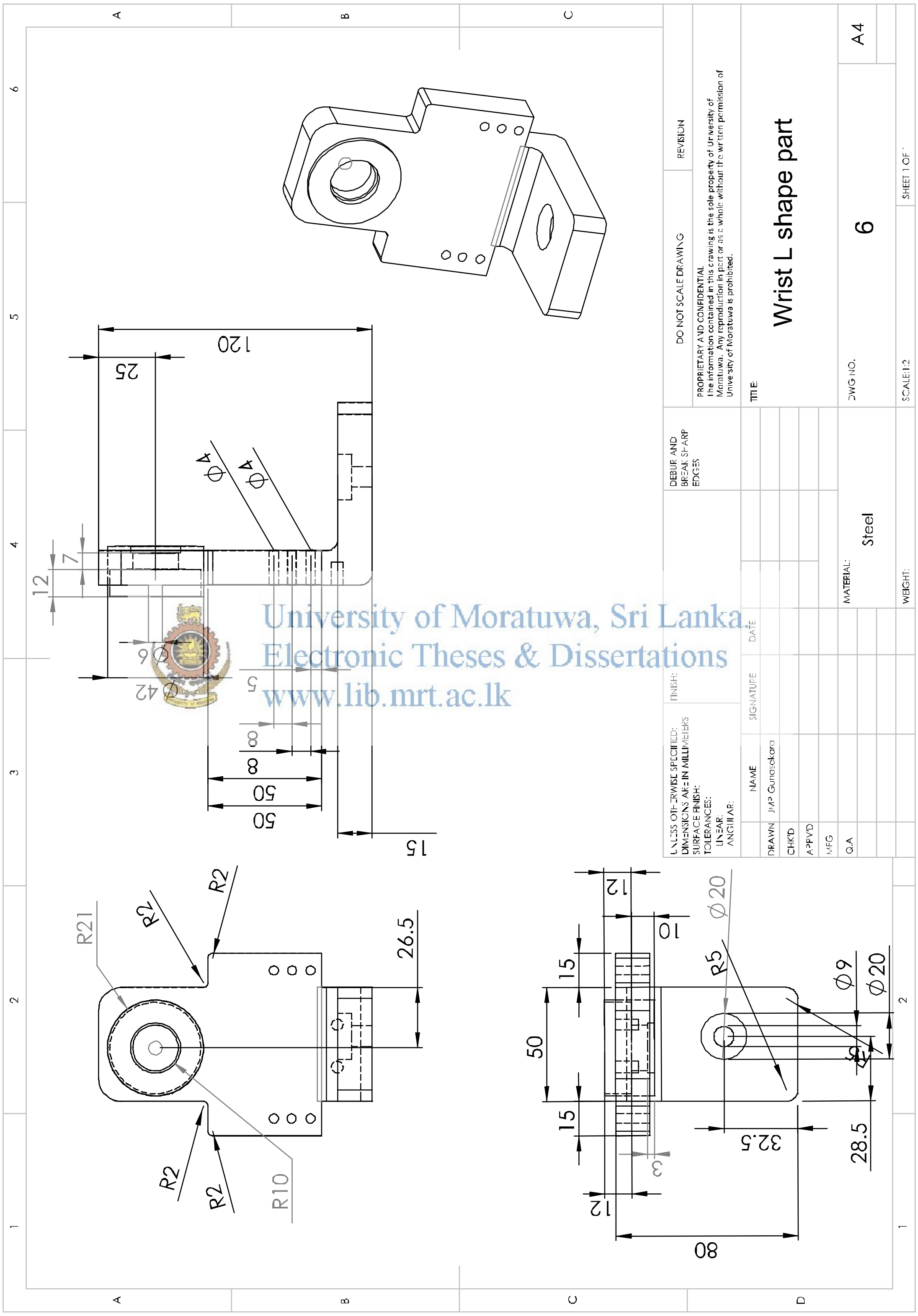


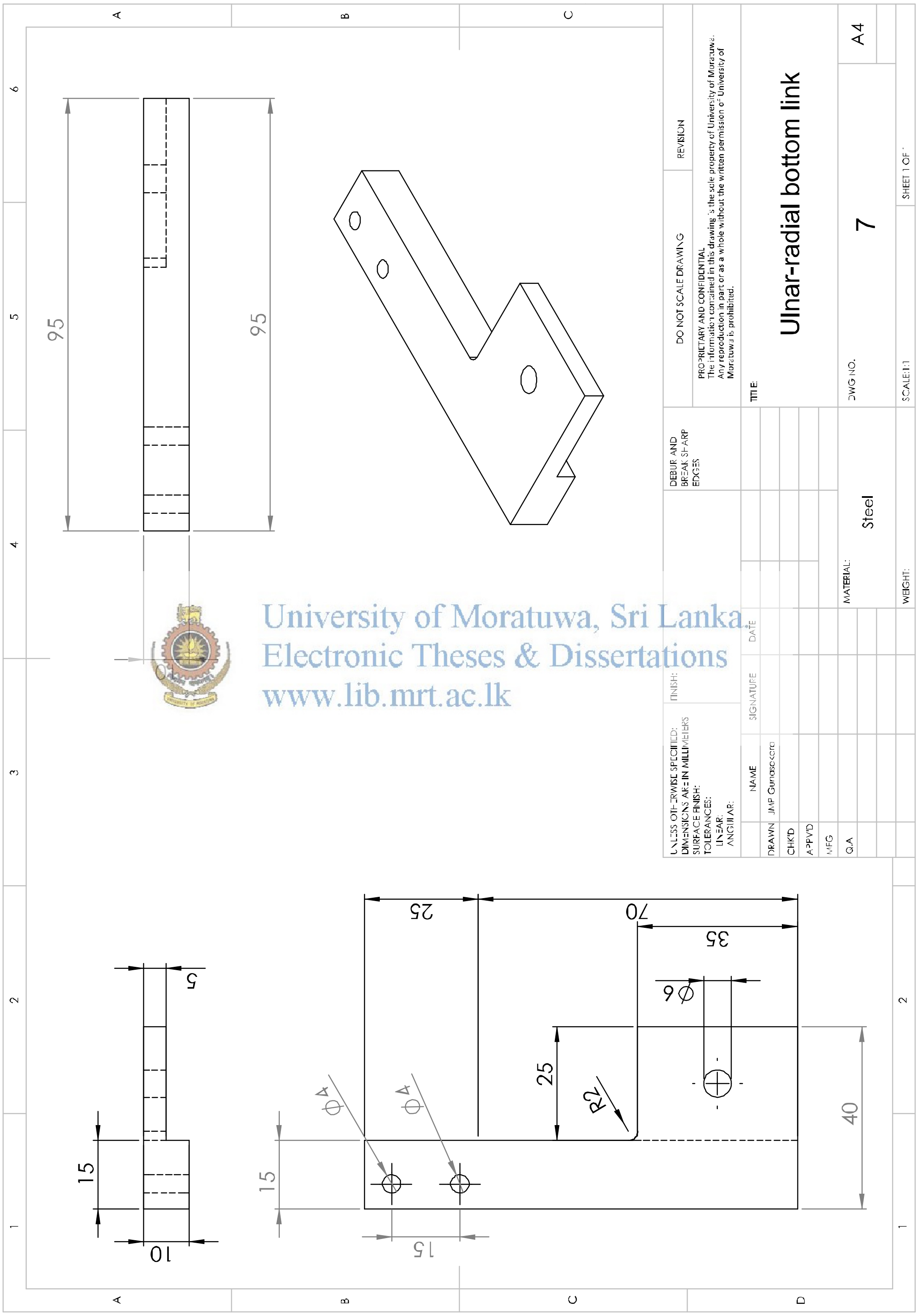
Supination fixed guide
DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
TITLE:
DWG NO.
2
A4
SCALE:1:2
MATERIAL:
Steel
WEIGHT:
DEBUR AND BREAK SHARP EDGES
NAME
SIGNATURE
DATE
DRAWN
JMP Gunasekara
CHK'D
APPV'D
MFG
Q.A
FINISH:
181
8
Ø190
Ø180
Ø5
Ø32.500
Ø5.500
10°
40
80
Ø170
220
10

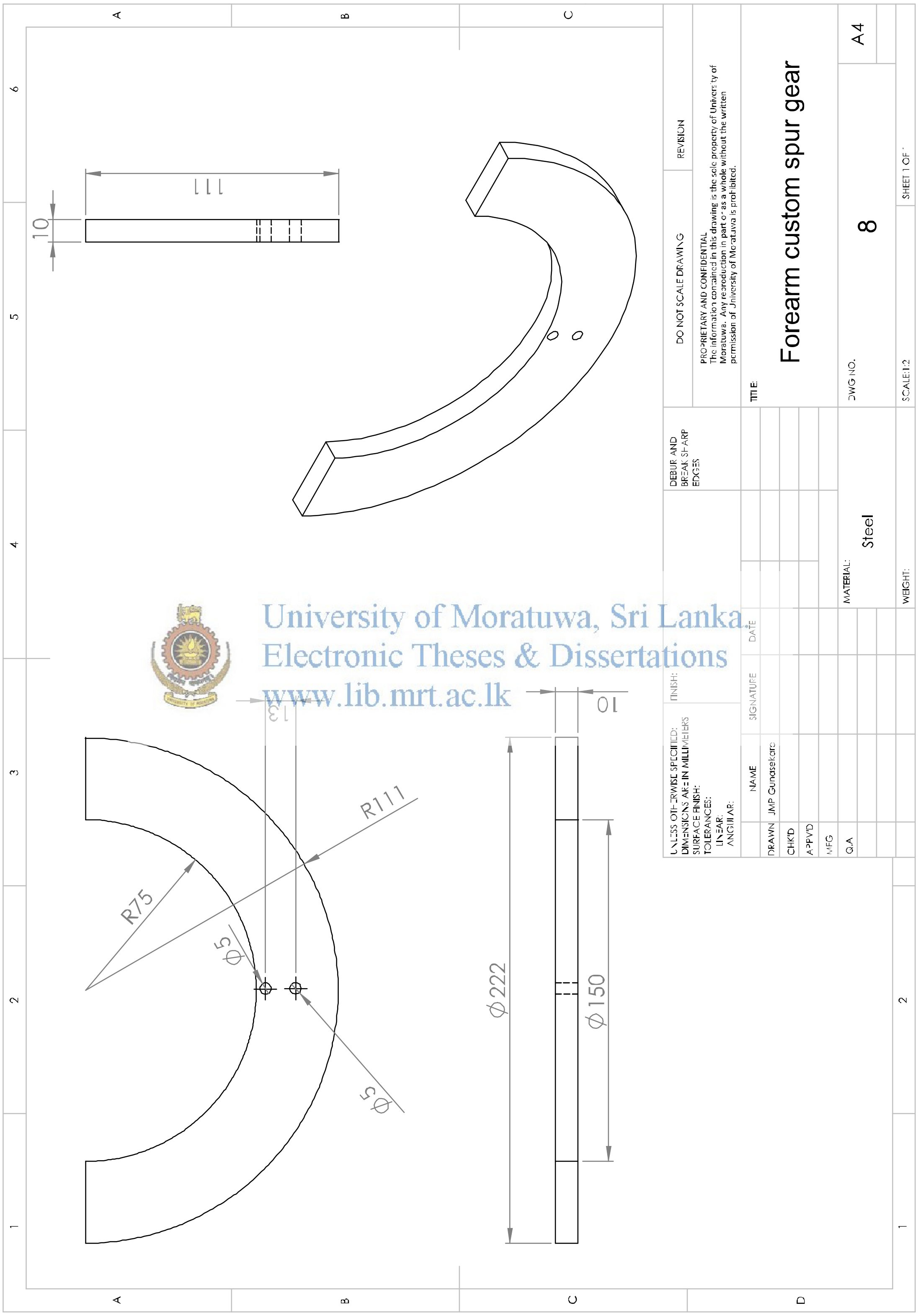

Back end support
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
DWG NO. 3
A4
SCALE:1:2
MATERIAL: Steel
WEIGHT:
DRAWN JMP Gunasekara
CHK'D
APPV'D
MFG
Q.A
NAME
SIGNATURE
DATE
FINISH:
DEBUR AND BREAK SHARP EDGES
REVISION
TITLE:
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

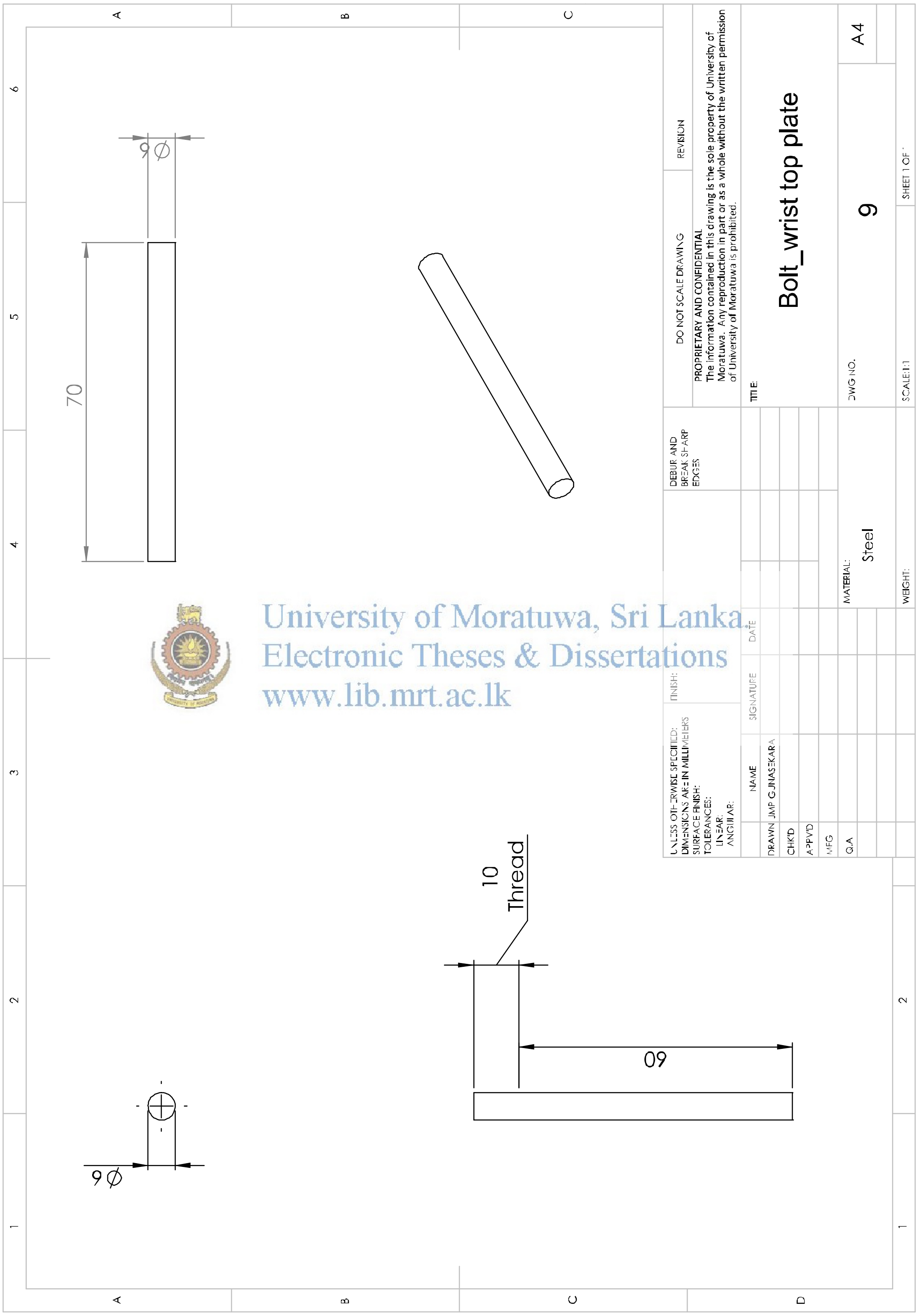

Circular sliding plate
DWG NO. 4
A4
SCALE:1:2
SHEET 1 OF 1
MATERIAL: Alloy Steel
WEIGHT:
DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
NAME
SIGNATURE
DATE
DRAWN JMP Gunasekara
CHK'D
APPV'D
MFG
Q.A
TITLE:
R75
R85
R95
10°
Ø5
Ø5
10
10
20
190
Ø170
Ø150
23
20
3
85
20
3


DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
TITLE:
L shape connecting link
DWG NO.
5
A4
SCALE:1:2
SHEET 1 OF 1
MATERIAL:
Steel
WEIGHT:
DEBUR AND BREAK SHARP EDGES
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:
FINISH:
NAME
SIGNATURE
DATE
DRAWN
JMP Gunasekara
CHK'D
APPV'D
MFG
Q.A
R2
8
Ø4
42
20
88
10
79
20
R10
13
70
90
40
5
100
15

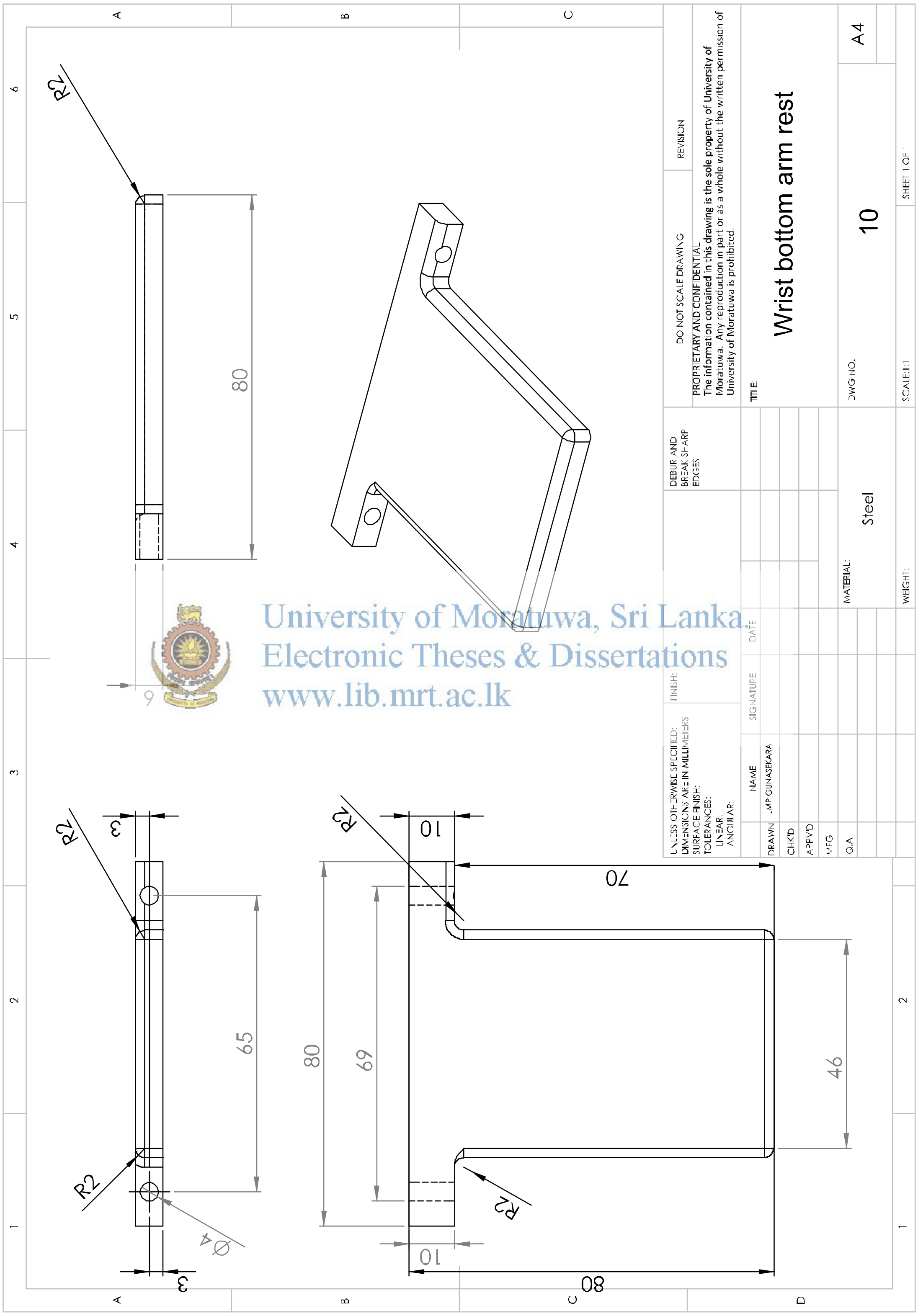

Wrist L shape part
DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
TITLE:
DWG NO.
6
A4
SCALE:1:2
SHEET 1 OF 1
MATERIAL:
Steel
WEIGHT:
DEBUR AND BREAK SHARP EDGES
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:
FINISH:
NAME
SIGNATURE
DATE
DRAWN
JMP Gunasekara
CHK'D
APPV'D
MFG
Q.A

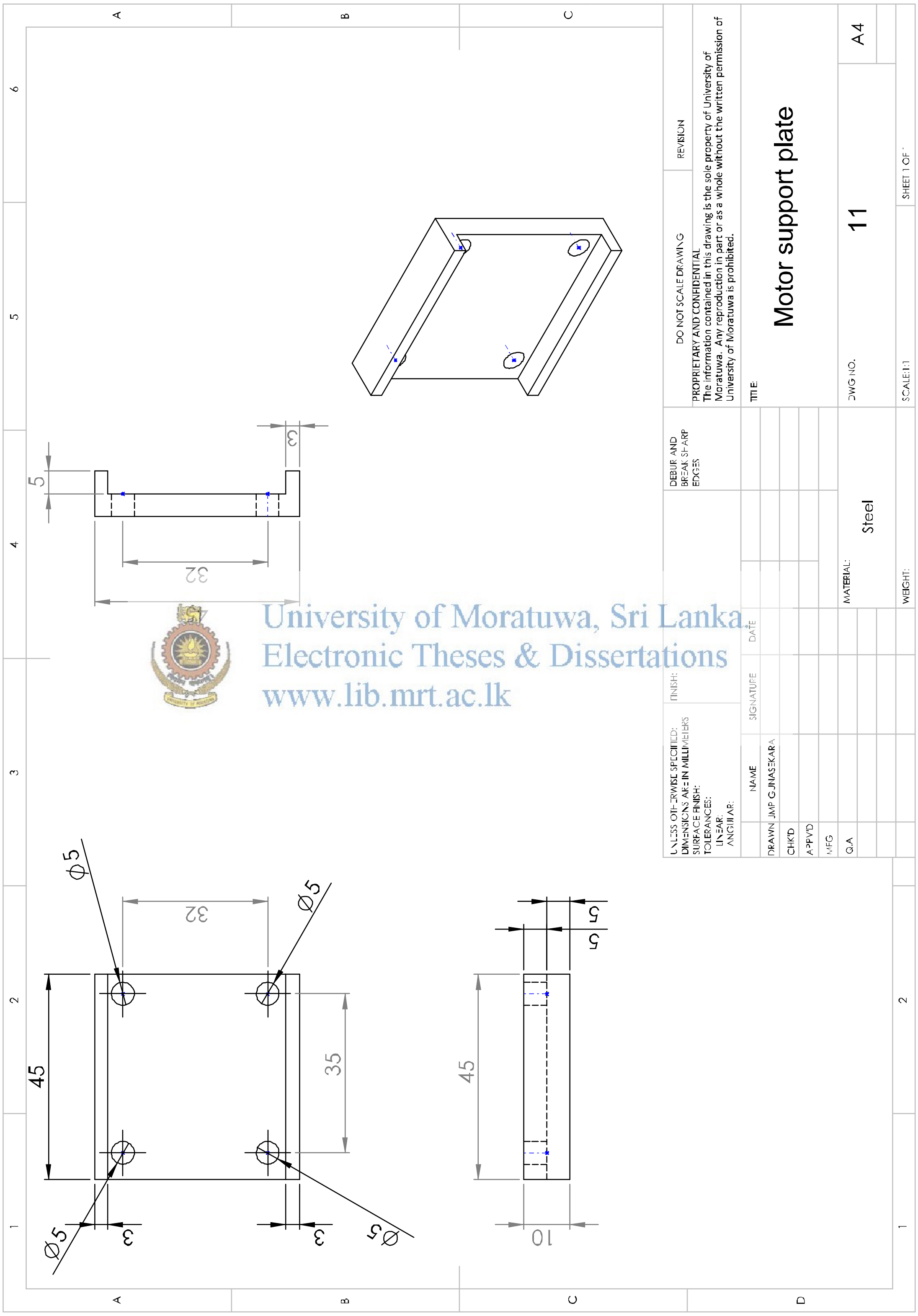

95
95
25
70
35
∅6
25
R2
40
∅4
∅4
15
15
5
10
15
DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
TITLE:
Ulnar-radial bottom link
DWG NO.
7
A4
SCALE:1:1
SHEET 1 OF 1
MATERIAL:
Steel
WEIGHT:
DEBUR AND BREAK SHARP EDGES
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:
FINISH:
NAME
SIGNATURE
DATE
DRAWN
JMP Gunasekera
CHK'D
APPV'D
MFG
Q.A


Forearm custom spur gear
DWG NO. 8
A4
MATERIAL: Steel
DRAWN JMP Gunasekara
SCALE:1:2
SHEET 1 OF 1
DO NOT SCALE DRAWING
REVISION
DEBUR AND BREAK SHARP EDGES
111
10
13
R111
R75
⌀5
⌀222
⌀150



9 ∅
70
10
Thread
60
DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
TITLE:
Bolt_wrist top plate
DWG NO.
9
A4
SCALE:1:1
MATERIAL:
Steel
WEIGHT:
DEBUR AND BREAK SHARP EDGES
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A


Wrist bottom arm rest
DWG NO. 10
A4
MATERIAL: Steel
SCALE:1:1
SHEET 1 OF 1
DRAWN MP GUNASEKARA
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS
DEBUR AND BREAK SHARP EDGES
R2
80
65
69
70
46
10
3
Ø4



Motor support plate
DO NOT SCALE DRAWING
REVISION
PROPRIETARY AND CONFIDENTIAL
The information contained in this drawing is the sole property of University of Moratuwa. Any reproduction in part or as a whole without the written permission of University of Moratuwa is prohibited.
TITLE:
DWG NO.
11
A4
SCALE:1:1
SHEET 1 OF
MATERIAL:
Steel
WEIGHT:
DEBUR AND BREAK SHARP EDGES
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
NAME
SIGNATURE
DATE
DRAWN
JMP GUNASEKARA
CHK'D
APPV'D
MFG
Q.A
45
35
32
Ø5
3
10
5

APPENDIX B

Matlab / Robotic Toolbox functions for 4DOF, 6-REXOS and Hand model

1. Defining 4DOF kinematic chain in RTB

```
L1=Link([0 163.74 0 0 ],'modified');
L2=Link([0 321.01 0 -pi/2 ],'modified');
L3=Link([0 035.87 0 -pi/2 ],'modified');
L4=Link([0 0 5 -pi/2 ],'modified');
robot.base=trotx(90,'deg');
robot.base=troty(90,'deg');
robot=SerialLink([L1 L2 L3 L4]);
```

2. Defining 6-REXOS kinematic chain in RTB

```
L1=Link([0 0 0 0 1],'modified');
L2=Link([0 163.74 0 0 0],'modified');
L3=Link([0 321.01 0 -pi/2 0],'modified');
L4=Link([0 35.87 0 -pi/2 0],'modified');
L5=Link([0 0 5 -pi/2 1],'modified');
L6=Link([0 0 0 0 0],'modified');
robot.base=trotx(90,'deg')
robot.base=troty(90,'deg')
robot=SerialLink([L1 L2 L3 L4 L5 L6]);
```


3. Defining human lower arm kinematic model in RTB

```
L1=Link([0 0 0 0],'modified');
L2=Link([0 0 250 -pi/2],'modified');
L3=Link([0 0.646 1.5 pi/2],'modified');
L4=Link([0 0 8 pi/2],'modified');
robot.base=troty(90,'deg');
robot.base=trotx(90,'deg');
robot=SerialLink([L1 L2 L3 L4]);
```

4. Joint trajectory generation

qi and qf refer to the initial and final joint configurations and divide the trajectory to 20 sample points

```
q=jtraj(qi,qf,20);
robot.plot(q);
```

5. Forward transformation matrix for all 20 steps in joint trajectory

```
T=robot.fkine(q);
X=squeeze(T(1,4,:));
Y=squeeze(T(2,4,:));
Z=squeeze(T(3,4,:));
plot3(X,Y,Z);
```

6. Forward transformation: symbolical evaluation_4DOF exoskeleton chain

```
syms c1 s1 c2 s2 c3 s3 c4 s4 L1 L2 L3 a3
to1=[c1 s1 0 0; -s1 c1 0 0; 0 0 1 L1; 0 0 0 1];
t12=[c2 s2 0 0; 0 0 1 L2; s2 c2 0 0; 0 0 0 1];
t23=[c3 -s3 0 0; 0 0 1 L3; -s3 -c3 0 0; 0 0 0 1];
t34=[c4 -s4 0 a3; 0 0 1 0; -s4 -c4 0 0; 0 0 0 1];
t04=to1*t12*t23*t34;
```

7. Forward transformation: symbolical evaluation_6-REXOS exoskeleton chain

```
syms c2 s2 c3 s3 c4 s4 c6 s6 d1 d5 L1 L2 L3 a3
t01=[1 0 0 0; 0 1 0 0; 0 0 1 d1; 0 0 0 1];
t12=[c2 s2 0 0; -s2 c2 0 0; 0 0 1 L1; 0 0 0 1];
t23=[c3 s3 0 0; 0 0 1 L2; s3 -c3 0 0; 0 0 0 1];
t34=[c4 s4 0 0; 0 0 1 L3; s4 -c4 0 0; 0 0 0 1];
t45=[1 0 0 a3; 0 1 1 d5; 0 -1 0 0; 0 0 0 1];
t56=[c6 -s6 0 0; s6 c6 0 0; 0 0 1 0; 0 0 0 1];
t06=t01*t12*t23*t34*t45*t56;
```

8. Jacobian (symbolic)_4DOF exoskeleton robot

```
J=[L2*c1-a3*(c1*s3+c2*c3*s1)-L3*s2*s1 -a3*c1*c3*s2+L3*c1*c2 -
a3*(s1*c3+c1*c2*s3) 0; -L2*s1-a3*(c2*c3*c1-s3*s1)-L3*c1*s2
a3*c3*s1*s2-L3*s1*c2 -a3*(c1*c3-c2*s1*s3) 0; 0 a3*c3*c2-L3*s2 -
a3*s2*s3 0; 0 s1 c1*s2 -c3*s1-c1*c2*s3; 0 c1 -s1*s2 c2*s1*s3-c1*c3; 1 0 c2
-s2*s3];
J([4 5],:)=[]
pretty(J);
det(J);
```


9. Jacobian (symbolic)_ 6-REXOS exoskeleton robot

```
J=[0 L2*c2+a3*(c2*s4-s2*c3*c4)-d5*(c4*c2+s2*c3*s4)-L3*c2*s3 -
a3*c2*s3*c4-d5*c2*s3*s4+L3*c2*c3 a3*(s2*c4-
c2*c3*s4)+d5*(s4*s2+c2*c3*c4) c2*c3*s4-c4*s2 0; 0 -L2*s2-
a3*(s2*s4+c3*c4*c2)-d5*(c3*c2*s4-s2*c4)-L3*c2*s3
a3*s3*c4*s2+d5*s3*s2*s4-L3*s2*c3 a3*(c2*c4+c3*s4*s2)-d5*(c3*s2*c4-
c2*s4) -c2*c4-c3*s2*s4 0; 1 0 L1*s3+a3*c4*c3+d5*c3*s4 d5*s3*c4-
a3*s4*s3 s3*s4 0; 0 0 s2 c2*s3 0 c2*c3*s4-c4*s2; 0 0 c2 -s2*s3 0 -c2*c4-
c3*s2*s4; 0 1 0 -c3 0 s3*s4];
J(4:5,:)=[];
J(:,1)=[];
J(:,4)=[];
det(J);
```

10. Evaluation of Jacobian at each joint step (in RTB)

```
J=robot.jacob0(q(1,:))
```

```
J=robot.jacob0(q(2,:))
J=robot.jacob0(q(3,:))
:         :         :         :         :         :
:         :         :         :         :         :
:         :         :         :         :         :
J=robot.jacob0(q(20,:))
```

11. Manipulability index measure

```
J=robot.jacob0(q(1,:));
J=J(1:3,:);
J';
sqrt(J*J');

J=robot.jacob0(q(2,:));
J=J(1:3,:);
J';
sqrt(J*J')
:         :         :         :         :
:         :         :         :         :
J=robot.jacob0(q(20,:));
J=J(1:3,:);
J';
sqrt(J*J')
```

12. Singular values of Jacobian


```
J=robot.jacob0(q(1,:));
J=J(1:3,:);
svd(J);
J=robot.jacob0(q(2,:));
J=J(1:3,:);
svd(J);
:         :         :         :         :         :
:         :         :         :         :         :
J=robot.jacob0(q(20,:));
J=J(1:3,:);
svd(J);
```

13. Condition number for translational Jacobian

```
J=robot.jacob0(q(1,:));
J=J(1:3,:);
cond(J);
J=robot.jacob0(q(2,:));
J=J(1:3,:);
cond(J);
:         :         :         :         :
:         :         :         :         :
J=robot.jacob0(q(20,:));
```

```
J=J(1:3,:);
cond(J);
```

14. Manipulability ellipsoids

```
J=robot.jacob0(q(1,:));
J=J(1:3,:);
plot_ellipse(J*J');
view(-60,20);
J=robot.jacob0(q(2,:));
J=J(1:3,:);
plot_ellipse(J*J');
view(-60,20);
:       :       :       :       :
:       :       :       :       :
J=robot.jacob0(q(20,:));
J=J(1:3,:);
plot_ellipse(J*J');
view(-60,20);
```

15. Manipulability index in entire workspace_4DOF exoskeleton robot

```
L2=321.01;
L3=35.87;
a3=5;
q2=linspace(-pi/3,pi/6,50);
q3=linspace(-pi/6,pi/6,50);
[q2,q3]=meshgrid(q2,q3);
Z=L2*L3*a3.*sin(q2).*cos(q3);
surfc((Z));
```


16. Manipulability index in entire workspace_6-REXOS exoskeleton robot

```
L3=35.87;
L1=163.74;
L2=321.01;
q3=linspace(-pi/3,pi/6,50);
q4=linspace(-pi/6,pi/6,50);
[q3,q4]=meshgrid(q3,q4);
z=L2.*sin(2*q4)-0.5*L3.*sin(2*q3).*cos(q4)^2;
surfc(z);
```

17. Evaluation of motor torques for 6-REXOS

```
Link mass
L1.m=.016;
L2.m=.6;
L3.m=1.339;
L4.m=0.5437;
L5.m=0.019;
L6.m=0.016;
```

Link centre of mass position

```
L1.r=[-0.01 0 -15.28];
L2.r=[80.30 -0.28 82.19];
L3.r=[-24.65 52.79 179.97];
L4.r=[-23.56 -28.08 6.01];
L5.r=[1.48 -27.13 -43.96];
L6.r=[0.28 0.52 10.26];
```

Moment of inertia about centre of mass

```
L1.I=[1.09 1.09 0.41 0.0 0.0 0.0];
L2.I=[3979.73 2866.28 2230.37 -1.48 -56.62 526.63];
L3.I=[7023.3 7422.82 1810.47 84.41 -96.64 -27.49];
L4.I=[937.6 775.01 356.87 0.78 -59.41 8.03];
L5.I=[386.97 348.15 178.89 9.57 -14.0 14.60];
L6.I=[1.09 1.09 0.41 0.0 0.03 0.02];
```

Inverse dynamics

```
grav=[0 0 9.81]';
tau_g=robot.rne(q,qd,qdd,grav);

plot(q(:,1),tau_g(:,1));
plot(q(:,2),tau_g(:,2));
plot(q(:,3),tau_g(:,3));
plot(q(:,4),tau_g(:,4));
```


Evaluation of accelerations at each joint (based on Walker and Orion method)

```
qdd=robot.accel(q,qd,tau_g);
```

APPENDIX_C

Table C-1: Numerical description for figures

Joint Position	Fig. 4.14: Manipulability of 6-REXOS	Fig. 4.16: Minimum singular value 6-REXOS	Fig.4.17: Condition number,6 REXOS	Fig.5.6 Manipulability of hand model	Fig 5.7 Manipulability variation for different wrist parameters		
					Hand_minimum	Hand_average	Hand_maximum
1	15910.69	1.54	209.07	16900.26	16392.16	16900.26	17408.66
2	15917.73	1.55	208.75	16867.96	16361.16	16867.96	17375.06
3	15957.69	1.56	206.73	16659.35	16160.86	16659.35	17158.16
4	16019.92	1.60	202.18	16131.19	15653.05	16131.18	16609.66
5	16011.59	1.65	195.33	15149.17	14706.83	15149.17	15591.87
6	15742.20	1.72	187.38	13578.33	13189.27	13578.33	13967.76
7	14954.82	1.79	179.99	11305.48	10987.90	11305.48	11623.41
8	13413.20	1.84	174.75	8287.36	8058.55	8287.36	8516.47
9	11023.93	1.86	172.98	4601.40	4475.81	4601.40	4727.15
10	7935.18	1.83	175.75	467.65	454.93	468.65	480.40
11	4540.87	1.74	184.00	3504.08	3504.09	3504.07	3507.23
12	1392.04	1.80	178.62	6651.18	6651.21	6651.18	6657.17
13	1390.34	1.94	164.78	7867.95	7867.98	7867.94	7875.03
14	4698.68	1.90	168.37	8767.35	8767.39	8767.35	8775.24
15	6281.50	1.85	172.78	9084.12	9084.17	9084.12	9092.30
16	7116.63	1.81	176.97	9461.54	9461.59	9461.55	9470.06
17	7531.65	1.77	180.32	9854.77	9854.82	9854.77	9863.64
18	7729.88	1.75	182.45	9978.86	9978.91	9978.86	9987.84
19	7805.85	1.74	183.37	10256.07	10256.12	10256.07	10265.30
20	7817.59	1.74	183.52	103355.75	10355.79	10355.74	10365.07