

<b>Table of Contents</b>	<b>Page No.</b>
List of figures .....	xiii
List of tables .....	xvii
List of abbreviations .....	xix
Preface .....	xxii
<b>Chapter 1</b>	
<b>Introduction.....</b>	<b>01</b>
<b>1.1 Amputation.....</b>	<b>02</b>
<b>1.1.1 Upper-limb amputation.....</b>	<b>02</b>
<b>1.1.2 Amputation scenario.....</b>	<b>02</b>
<b>1.2 Prosthesis .....</b>	<b>04</b>
<b>1.2.1 Upper-limb prosthesis.....</b>	<b>04</b>
<b>1.2.1.1 Body-powered prosthesis .....</b>	<b>05</b>
<b>1.2.1.2 Externally powered prosthesis .....</b>	<b>05</b>
<b>1.3 Electromyography.....</b>	<b>06</b>
<b>1.4 Myoelectric prosthesis .....</b>	<b>09</b>
<b>1.5 Myoelectric control system.....</b>	<b>10</b>
<b>1.6 Literature survey .....</b>	<b>11</b>
<b>1.7 Market overview .....</b>	<b>18</b>
<b>1.8 Problems .....</b>	<b>20</b>
<b>1.9 Research objectives.....</b>	<b>20</b>
<b>1.10 Thesis outline.....</b>	<b>21</b>
<b>1.11 References.....</b>	<b>24</b>
<b>Chapter 2</b>	
<b>A low-cost, wearable sEMG sensor for upper-limb prosthetic application.....</b>	<b>28</b>
<b>2.1 Introduction.....</b>	<b>29</b>
<b>2.2 Materials and methods .....</b>	<b>32</b>
<b>2.2.1 Design and construction of the sensor .....</b>	<b>32</b>
<b>2.2.1.1 Design of skin interface .....</b>	<b>33</b>
<b>2.2.1.2 Design of signal conditioning circuitry .....</b>	<b>33</b>
<b>2.2.1.3 Power supply unit .....</b>	<b>35</b>
<b>2.2.1.4 Description of the developed sensor .....</b>	<b>35</b>

<b>2.2.2 Experimental setup for sensor validation .....</b>	<b>36</b>
<b>2.2.2.1 Selecting a sensor for comparison .....</b>	<b>36</b>
<b>2.2.2.2 Subject selection .....</b>	<b>37</b>
<b>2.2.2.3 Allocating different levels of muscular contraction .....</b>	<b>38</b>
<b>2.2.2.4 Positioning of sensors .....</b>	<b>40</b>
<b>2.2.2.5 Data acquisition .....</b>	<b>40</b>
<b>2.3 Results and discussion .....</b>	<b>41</b>
<b>2.3.1 Amplitude analysis.....</b>	<b>41</b>
<b>2.3.2 Signal-to-noise ratio (SNR) calculation.....</b>	<b>42</b>
<b>2.3.3 Sensitivity analysis .....</b>	<b>44</b>
<b>2.3.4 Response time analysis.....</b>	<b>45</b>
<b>2.4 Sensor application for controlling prosthetic hand.....</b>	<b>46</b>
<b>2.4.1 Development of prosthetic hand prototype.....</b>	<b>46</b>
<b>2.4.2 Implementation of a control strategy for the generation of control command using the EMG signal from the sensor .....</b>	<b>47</b>
<b>2.4.3 Utilization of the sensor on amputees to control the operation of the prosthetic hand .....</b>	<b>48</b>
<b>2.5 Conclusion .....</b>	<b>49</b>
<b>2.6 References.....</b>	<b>52</b>
<b>Chapter 3</b>	
<b>A dry electrode-based compact-sized sEMG Sensor for myoelectric hand prosthesis .....</b>	<b>56</b>
<b>3.1 Introduction.....</b>	<b>57</b>
<b>3.2 Materials and methods .....</b>	<b>59</b>
<b>3.2.1 Design and development of sEMG sensor.....</b>	<b>59</b>
<b>3.2.1.1 Fabrication of electrode interface .....</b>	<b>59</b>
<b>3.2.1.2 Design of preprocessing circuitry .....</b>	<b>60</b>
<b>3.2.1.3 Sensor description .....</b>	<b>60</b>
<b>3.2.2 Experimental setup for Assessment of sensor performance.....</b>	<b>61</b>
<b>3.2.2.1 Selection of sensor for comparison .....</b>	<b>61</b>
<b>3.2.2.2 Positioning of sensors .....</b>	<b>62</b>
<b>3.2.2.3 Defining the level of muscular contraction .....</b>	<b>63</b>
<b>3.2.2.4 Data acquisition .....</b>	<b>65</b>
<b>3.3 Results and discussion .....</b>	<b>65</b>

<b>3.3.1 Electrode performance .....</b>	<b>65</b>
<b>3.3.1.1 Electrode-skin impedance .....</b>	<b>65</b>
<b>3.3.1.2 Electrode SNR .....</b>	<b>67</b>
<b>3.3.2 Sensor overall performance .....</b>	<b>67</b>
<b>3.3.2.1 Output .....</b>	<b>67</b>
<b>3.3.2.2 SNR .....</b>	<b>68</b>
<b>3.3.2.3 Sensitivity .....</b>	<b>70</b>
<b>3.3.2.4 Response time .....</b>	<b>71</b>
<b>3.4 Sensor utilization for prosthetic hand control.....</b>	<b>73</b>
<b>3.5 Conclusion .....</b>	<b>75</b>
<b>3.6 References.....</b>	<b>79</b>
<b>Chapter 4</b>	
<b>Single-channel sEMG based control of multi-functional prosthetic hand.....</b>	<b>82</b>
<b>4.1 Introduction.....</b>	<b>83</b>
<b>4.2. Materials and methods .....</b>	<b>85</b>
<b>4.2.1 Electromyography.....</b>	<b>85</b>
<b>4.2.1.1 EMG sensor .....</b>	<b>85</b>
<b>4.2.1.2 Muscle contractile force .....</b>	<b>86</b>
<b>4.2.1.3 Sensor attachment to the forearm.....</b>	<b>87</b>
<b>4.2.2 Subjects .....</b>	<b>88</b>
<b>4.2.3 Experimental protocol and data acquisition.....</b>	<b>89</b>
<b>4.2.4 Feature Extraction .....</b>	<b>89</b>
<b>4.2.5 Classification .....</b>	<b>91</b>
<b>4.2.5.1 Design of classifier .....</b>	<b>92</b>
<b>4.2.5.2 Classifier's performance .....</b>	<b>93</b>
<b>4.2.6 Real-time implementation and testing .....</b>	<b>94</b>
<b>4.2.6.1 Prosthetic hand development .....</b>	<b>94</b>
<b>4.2.6.2 Control scheme .....</b>	<b>95</b>
<b>4.2.6.3 Method for testing and analysis .....</b>	<b>96</b>
<b>4.3 Results .....</b>	<b>97</b>
<b>4.3.1 Sensor output.....</b>	<b>97</b>
<b>4.3.2 Extracted features .....</b>	<b>98</b>

<b>4.3.3 Classification performance.....</b>	<b>98</b>
<b>4.3.4 Real-time testing of multifunctional prosthetic hand .....</b>	<b>100</b>
<b>4.4 Discussion.....</b>	<b>103</b>
<b>4.5 Conclusion .....</b>	<b>105</b>
<b>4.6 References.....</b>	<b>107</b>
<b>Chapter 5</b>	
<b>A novel force myography sensor to measure muscle contraction for controlling hand prosthesis .....</b>	<b>111</b>
<b>    5.1 Introduction.....</b>	<b>112</b>
<b>    5.2 Materials and methods .....</b>	<b>115</b>
<b>5.2.1 Design of FMG Sensor .....</b>	<b>115</b>
<b>5.2.2 Signal conditioning .....</b>	<b>118</b>
<b>5.2.3 Static and dynamic characteristics of the FMG sensor .....</b>	<b>121</b>
<b>5.2.4 Similarity with the EMG signal .....</b>	<b>123</b>
<b>5.2.5 Controlling hand prosthesis .....</b>	<b>124</b>
<b>    5.3 Results and discussion .....</b>	<b>125</b>
<b>5.3.1 Static and dynamic results .....</b>	<b>125</b>
<b>5.3.2 EMG-FMG comparison .....</b>	<b>129</b>
<b>5.3.3 Hand prosthesis control.....</b>	<b>131</b>
<b>    5.4 Conclusion .....</b>	<b>132</b>
<b>    5.5 References .....</b>	<b>134</b>
<b>Chapter 6</b>	
<b>Development of an affordable transradial prosthesis based on force myography.....</b>	<b>138</b>
<b>    6.1 Introduction.....</b>	<b>139</b>
<b>    6.2 Materials and methods .....</b>	<b>142</b>
<b>6.2.1 Fabrication of sensor .....</b>	<b>142</b>
<b>6.2.2 Sensor validation.....</b>	<b>144</b>
<b>6.2.2.1 Sensitivity .....</b>	<b>145</b>
<b>6.2.2.2 Repeatability .....</b>	<b>145</b>
<b>6.2.2.3 Hysteresis .....</b>	<b>145</b>
<b>6.2.2.4 Frequency response .....</b>	<b>145</b>
<b>6.2.2.5 Correlation with EMG signal .....</b>	<b>146</b>
<b>6.2.2.6 SNR calculation .....</b>	<b>146</b>
<b>    6.2.3 Prosthetic hand development.....</b>	<b>147</b>

<b>6.2.3.1 3D printing .....</b>	<b>147</b>
<b>6.2.3.2 Actuation .....</b>	<b>147</b>
<b>6.3 Results and discussion .....</b>	<b>148</b>
<b>6.3.1 Sensitivity.....</b>	<b>148</b>
<b>6.3.2 Repeatability.....</b>	<b>149</b>
<b>6.3.3 Hysteresis .....</b>	<b>150</b>
<b>6.3.4 Frequency response curve .....</b>	<b>150</b>
<b>6.3.5 FMG-EMG correlation.....</b>	<b>150</b>
<b>6.3.6 SNR comparison.....</b>	<b>152</b>
<b>6.4 Hand prosthesis control.....</b>	<b>152</b>
<b>6.4.1 Control scheme.....</b>	<b>152</b>
<b>6.4.2 Complete hand setup .....</b>	<b>153</b>
<b>6.4.3 Hand trial on amputees .....</b>	<b>154</b>
<b>6.5 Conclusion .....</b>	<b>156</b>
<b>6.6 References.....</b>	<b>158</b>
<b>Chapter 7</b>	
<b>Conclusions and future scope .....</b>	<b>162</b>
<b>7.1 Conclusions.....</b>	<b>163</b>
<b>7.2 Future scope .....</b>	<b>164</b>
<b>Permission from Ethical Committee.....</b>	<b>165</b>
<b>List of publications .....</b>	<b>166</b>

## LIST OF FIGURES

---

<b>Figure No.</b>	<b>Figure description</b>	<b>Page No.</b>
<b>Figure 1.1</b>	Different types of upper-limb amputation.	03
<b>Figure 1.2</b>	Statistics of amputees around the world.	03
<b>Figure 1.3</b>	Different types of upper-limb prosthesis.	04
<b>Figure 1.4</b>	Different types of upper-limb functional prosthesis.	06
<b>Figure 1.5</b>	Generation of EMG signal.	07
<b>Figure 1.6</b>	Placement of electrodes for performing surface electromyography.	08
<b>Figure 1.7</b>	Description of EMG measuring devices.	09
<b>Figure 1.8</b>	The various components of a myoelectric prosthesis.	10
<b>Figure 1.9</b>	Types of myoelectric control system.	11
<b>Figure 1.10</b>	(a) Manus hand intrinsically actuated using two DC motors, (b) Smart hand actuated by four motors.	13
<b>Figure 1.11</b>	(a) Modular prosthetic limb intrinsically actuated by fifteen motors, (b) Southampton hand-activated using six motors.	14
<b>Figure 1.12</b>	(a) Deka arm from defence advanced research project agency, (b) Hit prosthetic hand, (c) A dexterous hand actuated by seventeen motors.	15
<b>Figure 1.13</b>	An anthropomorphic, single-channel sEMG controlled prosthetic hand, (b) 3D-printed myoelectric prosthesis with individual finger operation.	16
<b>Figure 1.14</b>	Commercially available (a) Michelangelo hand, (b) Ottobock sensor hand, (c) i-Limb quantum hand, (d) Bebionic v3 hand.	18
<b>Figure 1.15</b>	Flowchart representation of thesis outline.	23
<b>Figure 2.1</b>	Block diagram representation of the proposed EMG sensor.	33
<b>Figure 2.2</b>	(a) Envelope detector circuit, (b) Circuit for step-up booster and single to dual supply.	36
<b>Figure 2.3</b>	(a) Front view of the sensor, (b) Rear view of the sensor showing the skin interface.	36
<b>Figure 2.4</b>	(a) Sensing area of the FSR band, (b) Output circuit for the band, (c) Attachment of band to the forearm.	38
<b>Figure 2.5</b>	Force voltage calibration curve for the FSR band.	39

<b>Figure 2.6</b>	Attachment of sensors on the forearm of subjects.	40
<b>Figure 2.7</b>	Raw EMG and its envelope obtained by the sensor.	41
<b>Figure 2.8</b>	Obtained EMG Signal envelopes with (a) Developed sensor, (b) Myoware muscle sensor.	42
<b>Figure 2.9</b>	EMG output voltage vs. movement repetition for (a) developed sensor (b) myoware sensor.	42
<b>Figure 2.10</b>	Noise level and EMG signal envelope obtained using developed sensor.	42
<b>Figure 2.11</b>	(a) Sensitivity comparison of sensors for all the subjects, (b) Sensitivity comparison of sensors for amputees.	45
<b>Figure 2.12</b>	Rise and fall time calculation from the envelope produced with the developed sensor.	46
<b>Figure 2.13</b>	Prepared 3D printed hand prototype.	47
<b>Figure 2.14</b>	Schematic for generating the control command.	48
<b>Figure 2.15</b>	Performed operations by prosthetic hand using sEMG signal from amputees.	49
<b>Figure 3.1</b>	(a) Dry type surface myoelectrodes, (b) wet type surface myoelectrodes.	57
<b>Figure 3.2</b>	(a) Block diagram representation of the proposed EMG sensor, (b) detailed circuit for the envelope detector.	60
<b>Figure 3.3</b>	(a) Front view of the developed sensor, (b) Rear view of the developed sensor.	61
<b>Figure 3.4</b>	Attachment of (a) developed sensor on healthy subject, (b) conventional sensor on healthy subject (c), (d) developed sensor on amputees.	62
<b>Figure 3.5</b>	(a) Sensing area of the FSR band, (b) Output circuit for the band, (c) Attachment of band to the forearm, (d) Attachment of the developed sensor and band together to the forearm.	64
<b>Figure 3.6</b>	Force voltage calibration curve for FSR band.	64
<b>Figure 3.7</b>	Obtained impedance response for both the surface electrodes.	66
<b>Figure 3.8</b>	Envelopes produced by the two sensors for six different levels of muscular contractions of an amputee.	68
<b>Figure 3.9</b>	(a) SNR calculation from recorded EMG envelope, (b) Baseline noise for myoware sensor, (c) Baseline noise for developed sensor.	69
<b>Figure 3.10</b>	(a) Sensitivities of sensors for all the subjects, (b) Sensitivities of sensors for only amputees.	71

<b>Figure 3.11</b>	Rise and fall time calculation from an EMG envelope.	72
<b>Figure 3.12</b>	Generation of control command using EMG signal from the sensor.	73
<b>Figure 3.13</b>	Grasping of various objects performed by prosthetic hand using EMG signals from an amputee.	74
<b>Figure 4.1</b>	Block diagram of the sensor showing different stages.	86
<b>Figure 4.2</b>	(a) FSR band, (b) translating circuit, (c) attachment of FSR band on forearm.	87
<b>Figure 4.3</b>	(a) Sensor attached on the forearm muscles of a transradial amputee, (b) attachment of sensor and FSR band together on the forearm muscles.	88
<b>Figure 4.4</b>	Block diagram for Fuzzy logic classification based control scheme.	93
<b>Figure 4.5</b>	(a) Developed 3D printed hand prototype, (b) experimental setup for real-time operation of hand.	95
<b>Figure 4.6</b>	The control scheme for real-time control of developed prosthetic hand.	96
<b>Figure 4.7</b>	EMG envelopes for six levels of muscular contraction using the designed sensor.	97
<b>Figure 4.8</b>	3D plot for variation of (a) MAV, (b) IEMG, (c) MAX, (d) RMS with different muscular contraction levels for all the subjects.	98
<b>Figure 4.9</b>	Six predefined grip patterns of human hand and the grip patterns obtained by prosthetic hand.	101
<b>Figure 4.10</b>	Different grasping actions performed by the prosthetic hand utilizing EMG signal from a subject.	101
<b>Figure 4.11</b>	Variation of response time of prosthetic hand for performing each grip pattern considering all the subject.	103
<b>Figure 5.1</b>	Construction of FSR showing its different layers.	116
<b>Figure 5.2</b>	Mechanical arrangement for uniform distribution of force on the FSR.	118
<b>Figure 5.3</b>	(a) Buffered voltage divider, (b) bipolar supply circuitry, (c) buck converter, (d) transimpedance amplifier.	119
<b>Figure 5.4</b>	Designed FMG sensor (a) front view, (b) rear view, (c) side view.	120
<b>Figure 5.5</b>	Experimental arrangement for the measurement of the frequency response of the designed FMG sensor.	122
<b>Figure 5.6</b>	Placement of FMG sensor and EMG sensor on the forearm muscle of a subject.	123

<b>Figure 5.7</b>	Controlling 3D printed hand prosthesis using the FMG signal of an amputee.	125
<b>Figure 5.8</b>	Static calibration curve for the FMG sensor.	126
<b>Figure 5.9</b>	Recorded output of the sensor for 120 s after application of different static loads.	126
<b>Figure 5.10</b>	FMG sensor drift error at different applied weights.	127
<b>Figure 5.11</b>	Hysteresis curve obtained for the sensor.	127
<b>Figure 5.12</b>	Repeatability error of the sensor at different loads.	128
<b>Figure 5.13</b>	Dynamic response of the sensor: magnitude frequency response (upper panel) and phase frequency response (lower panel).	129
<b>Figure 5.14</b>	Simultaneous recordings of (a) raw EMG signal, (b) linear envelope of EMG, (c) FMG sensor output for three different contractions of forearm muscle of decreasing intensity.	130
<b>Figure 5.15</b>	Different grasping operations performed by an amputee wearing hand prosthesis.	131
<b>Figure 6.1</b>	(a) Mechanical assembly of the proposed FMG sensor, (b) front, rear, and side views of the designed FMG sensor.	143
<b>Figure 6.2</b>	(a) Step-down converter circuit, (b) transimpedance amplifier.	144
<b>Figure 6.3</b>	Actuation scheme for the hand fingers.	148
<b>Figure 6.4</b>	Static calibration curve for the sensor.	149
<b>Figure 6.5</b>	Repeatability error curve for the sensor.	149
<b>Figure 6.6</b>	Hysteresis curve for the sensor.	150
<b>Figure 6.7</b>	The frequency response curve for the sensor.	151
<b>Figure 6.8</b>	Simultaneously acquired FMG and EMG envelopes for MVC, 50% MVC, and 25% MVC.	151
<b>Figure 6.9</b>	The control scheme for driving hand prototype.	153
<b>Figure 6.10</b>	Developed hand prototype showing different parts.	154
<b>Figure 6.11</b>	Attachment of developed prosthetic hand setup to the residual limb of an amputee.	155
<b>Figure 6.12</b>	Activities performed by an amputee wearing the developed hand.	155

## LIST OF TABLES

---

<b>Table No.</b>	<b>Table description</b>	<b>Page No.</b>
<b>Table 1.1</b>	Prosthetic hands developed by the researchers.	17
<b>Table 1.2</b>	Prosthetic hands commercially available in market.	19
<b>Table 2.1</b>	Commercially available EMG devices.	32
<b>Table 2.2</b>	Details of amputees participated for acquisition.	37
<b>Table 2.3</b>	Contraction level based on FSR output.	39
<b>Table 2.4</b>	Determined SNR by sensor type.	44
<b>Table 2.5</b>	Rise and fall time for the sensors.	46
<b>Table 2.6</b>	The response time of hand with both the sensors.	49
<b>Table 2.7</b>	Comparison table for the sensors.	50
<b>Table 3.1</b>	Details of amputees participated in EMG data acquisition.	61
<b>Table 3.2</b>	Contraction level determined from FSR output.	64
<b>Table 3.3</b>	Performance comparison for surface electrodes.	67
<b>Table 3.4</b>	Evaluated SNR by sensor type.	70
<b>Table 3.5</b>	Rise and fall time for both the sensors.	72
<b>Table 3.6</b>	Response time of hand with both the sensors.	75
<b>Table 3.7</b>	Specification for the sensors.	76
<b>Table 4.1</b>	Contraction levels for recording EMG data.	87
<b>Table 4.2</b>	Details of amputees participated in the experiment.	89
<b>Table 4.3</b>	Fuzzy rules.	92
<b>Table 4.4</b>	Achieved classification percentages for the six gestures.	99
<b>Table 4.5</b>	ROC analysis for each hand activities.	99

<b>Table 4.6</b>	Contingency matrices.	100
<b>Table 4.7</b>	Number of correct grip actions performed by the subjects.	102
<b>Table 6.1</b>	Evaluated SNR for both the sensors.	152
<b>Table 6.2</b>	Comparison of developed hand with a commercial hand.	157