Chapter 7
Conclusions and Future Research Directions

This chapter presents a conclusion to the work described in this doctoral dissertation. The main contributions are summarized, followed by some suggestions regarding future directions of research related to this work.

7.1 Concluding Remarks

The main thrust of this thesis is to enable the automatic monitoring of laser-induced changes on tissues during robot-assisted laser microsurgery. Two types of effects were studied: thermal (tissue temperature variation) and mechanical (creation of the incision crater). Surgeon control of these effects is crucial to surgical outcomes, yet these are difficult to perceive and require a significant amount of cognitive acuity. Computer and robot-assisted surgical systems should extend the surgeon performance beyond the limitations of human possibilities, not just in terms of what the surgeon is able to do, but also in the perception of relevant processes that are difficult or impossible to sense. Drawing on these practical problems, this doctoral dissertation focused on the development of models capable of describing the changes induced by surgical lasers on soft tissues, under the condition that these models must be compatible with use in a real surgical setting.

This dissertation successfully demonstrates the applicability of statistical learning methods to model the laser incision process during laser microsurgery. To the best of our knowledge, it is the first time that these techniques are applied in this field: analytical models constitute the traditional approach for the analysis of the interaction of the laser with the tissue [1]. With respect to existing approaches, our modeling methodology explicitly considers typical laser parameters used by clinicians during an intervention, (i.e. power, scanning frequency, energy delivery mode, incision length and laser exposure time), thus producing models that are straightforward to use in a surgical scenario either for monitoring or control applications.

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The key findings and novel contributions of this doctoral research are summarized below.

1. Definition of an approach to learn the superficial temperature of tissues during laser incision. The Gaussian temperature profile induced by a single TEM_{00} laser pulse is used as a basis function to represent the evolution of temperature in the area surrounding the ablation site (Sect. 4.2). The temperature variation induced by a scanning laser beam is modeled through the superposition of Gaussian functions (Sect. 4.3), achieving an average estimation error (Root-Mean-Square Error, RMSE) of 1.52 °C, and a maximum error of 2.62 °C.
2. Definition of an approach to learn the laser incision depth in soft tissues. Our approach extends existing empirical models by taking into account the individual effect of each laser parameter on the resulting incision depth (Sect. 5.2). The depth is modeled as a function of the laser exposure time. The approach was validated on ex-vivo chicken muscle tissue: it was found that a simple linear regression provides an adequate approximation of the relationship exposure time and the resulting incision depth (Sect. 5.3). Experimental validation reveals a RMSE of 0.10 mm, for incisions up to 1 mm in depth.
3. This dissertation explored the automatic control of the laser incision depth, based on a learned model that maps a desired incision depth to the laser exposure time required for its realization (Sect. 5.5). The achieved accuracy is (RMSE) 0.12 mm. In addition, we provided a novel strategy to implement the automatic ablation of entire volumes of tissue, based on the superposition of controlled laser incisions. This approach allows for the creation of ablations with pre-defined depth, with an accuracy (RMSE) of 0.17 mm.
4. A Cognitive Supervisory System (CS) prototype was developed and integrated in the μRALP surgical system. Based on the aforementioned models of temperature and incision depth, the CS endows the μRALP system with new functionalities that provide surgeons with additional information regarding the state of tissues during the execution of laser incision (Sect. 6.2):

    - The depth estimation is meant to guide the surgeon in the execution of precise tissue incisions.
    - The temperature estimation is intended to support his decisions in order to avoid thermal damage (e.g. carbonization).

7.2 Future Research Directions

The contributions in this dissertation can lead to new lines of inquiry in the area of robot-assisted laser surgery. Several new questions emerge in light of the discoveries presented here. A few of the most prominent are listed here.

7.2.1 Clinical Translation

Ex-vivo chicken muscle tissue was used to develop and validate the modeling approaches described in Chaps. 4 and 5. Translation of the presented research to clinical technologies requires one additional validation step, which is the creation of models capable of describing laser-induced changes in diverse human tissues (e.g. dermis, ligament). In-vitro models [2] seem a promising option for an initial validation: these are created by means of tissue engineering techniques that allow to replicate the composition and properties of real tissues.

7.2.2 Online Learning

A natural extension of the modeling methodologies proposed in this dissertation would be to explore on-line learning algorithms to build models that can be continuously improved, through the addition of new experimental data.

7.2.3 Automatic Control of Tissue Thermal Damage

The model of tissue temperature presented in Chap. 4 was implemented in the μRALP system. Activation and deactivation of the model is synchronized by the system, allowing online estimation of the temperature of the tissue surface. This thermal monitoring can be used to define policies to prevent thermal damage on the tissue. For instance, modification of the scanning frequency or deactivation of the laser exposure can be manipulated by the central system based on the output of the model.

7.2.4 Training of Laser Surgeons

Evidence presented in Sect. 6.3 seem to indicate that a numerical representation of the laser incision depth might help people with no prior experience of laser operations in conducting precise incisions. It would be interesting to investigate whether this could be exploited to support the training of prospective laser surgeons, specifically with respect to the the development of their laser cutting technique.

References

1. M. Niemz, *Laser-tissue Interactions* (Springer, Berlin, 2004)
2. F. Urciuolo, G. Imparato, A. Totaro, P.A. Netti, Building a tissue in vitro from the bottom up: implications in regenerative medicine. Methodist DeBakey Cardiovasc. J. **9**(4), 213 (2013)