

**ON THE LOCAL CONVERGENCE OF SEMISMOOTH
NEWTON METHODS FOR LINEAR AND NONLINEAR
SECOND-ORDER CONE PROGRAMS
WITHOUT STRICT COMPLEMENTARITY¹**

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Abstract

The optimality conditions of a nonlinear second-order cone program can be reformulated as a nonsmooth system of equations using a projection mapping. This allows the application of nonsmooth Newton methods for the solution of the nonlinear second-order cone program. Conditions for the local quadratic convergence of these nonsmooth Newton methods are investigated. Related conditions are also given for the special case of a linear second-order cone program. An interesting and important feature of these conditions is that they do not require strict complementarity of the solution. Some numerical results are included in order to illustrate the theoretical considerations.

Key Words: Linear second-order cone program, nonlinear second-order cone program, semismooth function, nonsmooth Newton method, quadratic convergence without strict complementarity

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1 Introduction

We consider both the linear second-order cone program (linear SOCP)

$$\min c^T x \quad \text{s.t.} \quad Ax = b, \quad x \in \mathcal{K}, \quad (1)$$

and the nonlinear second-order cone program (nonlinear SOCP)

$$\min f(x) \quad \text{s.t.} \quad Ax = b, \quad x \in \mathcal{K}, \quad (2)$$

where $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a twice continuously differentiable function, $A \in \mathbb{R}^{m \times n}$ is a given matrix, $b \in \mathbb{R}^m$ and $c \in \mathbb{R}^n$ are given vectors, and

$$\mathcal{K} = \mathcal{K}_1 \times \cdots \times \mathcal{K}_r$$

is a Cartesian product of second-order cones $\mathcal{K}_i \subseteq \mathbb{R}^{n_i}$, $n_1 + \cdots + n_r = n$. Recall that the second-order cone (or ice-cream cone or Lorentz cone) of dimension n_i is defined by

$$\mathcal{K}_i := \{x_i = (x_{i0}, \bar{x}_i) \in \mathbb{R} \times \mathbb{R}^{n_i-1} \mid x_{i0} \geq \|\bar{x}_i\|\},$$

where $\|\cdot\|$ denotes the Euclidean norm. Observe the special notation that is used in the definition of \mathcal{K}_i and that will be applied throughout this manuscript: For a given vector $z \in \mathbb{R}^\ell$ for some $\ell \geq 1$, we write $z = (z_0, \bar{z})$, where z_0 is the first component of the vector z , and \bar{z} consists of the remaining $\ell - 1$ components of z .

The linear SOCP has been investigated in many previous works, and we refer the interested reader to the two survey papers [18, 1] and the books [2, 4] for many important applications and theoretical properties. Software for the solution of linear SOCPs is also available, see, for example, [17, 28, 24, 27]. In many cases, the linear SOCP may be viewed as a special case of a (linear) semidefinite program (see [1] for a suitable reformulation). However, we feel that the SOCP should be treated directly since the reformulation of a second-order cone constraint as a semidefinite constraint increases the dimension of the problem significantly and, therefore, decreases the efficiency of any solver. In fact, many solvers for semidefinite programs (see, for example, the list given on Helmberg's homepage [14]) are able to deal with second-order cone constraints separately.

The treatment of the nonlinear SOCP is much more recent, and, in the moment, the number of publications is rather limited, see [3, 5, 6, 7, 8, 12, 13, 16, 25, 26, 29]. These papers deal with different topics; some of them investigate different kinds of solution methods (interior-point methods, smoothing methods, SQP-type methods, or methods based on unconstrained optimization), while some of them consider certain theoretical properties or suitable reformulations of the SOCP.

The method of choice for the solution of (at least) the linear SOCP is currently an interior-point method. However, some recent preliminary tests indicate that the class of smoothing or semismooth methods is sometimes superior to the class of interior-point

methods, especially for nonlinear problems, see [8, 13, 26]. On the other hand, the theoretical properties of interior-point methods are much better understood than those of the smoothing and semismooth methods.

The aim of this paper is to provide some results which help to understand the theoretical properties of semismooth methods being applied to both linear and nonlinear SOCPs. The investigation here is of local nature, and we provide sufficient conditions for those methods to be locally quadratically convergent. An interesting and important feature of those sufficient conditions is that they do not require strict complementarity of the solution. This is an advantage compared to interior-point methods where singular Jacobians occur if strict complementarity is not satisfied. Similar results were recently obtained in [15] (see also [11]) for linear semidefinite programs. In principle, these results can also be applied to linear SOCPs, but this requires a reformulation of the SOCP as a semidefinite program which, as mentioned above, is not necessarily the best approach, and therefore motivates a direct treatment of SOCPs. In fact, to the best of our knowledge, the algorithm investigated in this paper is currently the only one which deals with SOCPs directly and has the property of local quadratic convergence in the absence of strict complementarity.

The paper is organized as follows: Section 2 states a number of preliminary results for the projection mapping onto a second-order cone, which will later be used in order to reformulate the optimality conditions of the SOCP as a system of equations. Section 3 then investigates conditions that ensure the nonsingularity of the generalized Jacobian of this system, so that the nonsmooth Newton method is locally quadratically convergent. Some preliminary numerical examples illustrating the local convergence properties of the method are given in Section 4. We close with some final remarks in Section 5.

Most of our notation is standard. For a differentiable mapping $G : \mathbb{R}^n \rightarrow \mathbb{R}^m$, we denote by $G'(z) \in \mathbb{R}^{m \times n}$ the Jacobian of G at z . If G is locally Lipschitz continuous, the set

$$\partial_B G(z) := \{H \in \mathbb{R}^{m \times n} \mid \exists \{z^k\} \subseteq D_G : z^k \rightarrow z, G'(z^k) \rightarrow H\}$$

is nonempty and called the B-subdifferential of G at z , where $D_G \subseteq \mathbb{R}^n$ denotes the set of points at which G is differentiable. The convex hull $\partial G(z) := \text{conv} \partial_B G(z)$ is the generalized Jacobian of Clarke [9]. We assume that the reader is familiar with the concepts of (strongly) semismooth functions, and refer to [23, 22, 20, 10] for details. The identity matrix of order n is denoted by I_n .

2 Projection Mapping onto Second-Order Cone

Throughout this section, let \mathcal{K} be the single second-order cone

$$\mathcal{K} := \{z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1} \mid z_0 \geq \|\bar{z}\|\}.$$

In the subsequent sections, \mathcal{K} will be the Cartesian product of second-order cones. The results of this section will later be applied componentwise to each of the second-order cones \mathcal{K}_i in the Cartesian product.

Recall that the second-order cone \mathcal{K} is self-dual, i.e. $\mathcal{K}^* = \mathcal{K}$, where $\mathcal{K}^* := \{d \in \mathbb{R} \times \mathbb{R}^{n-1} \mid z^T d \geq 0 \ \forall z \in \mathcal{K}\}$ denotes the dual cone of \mathcal{K} , cf. [1, Lemma 1]. Hence the following result holds, see, e.g., [12, Proposition 4.1].

Lemma 2.1 *The following equivalence holds:*

$$x \in \mathcal{K}, y \in \mathcal{K}, x^T y = 0 \iff x - P_{\mathcal{K}}(x - y) = 0,$$

where $P_{\mathcal{K}}(z)$ denotes the (Euclidean) projection of a vector z on \mathcal{K} .

An explicit representation of the projection $P_{\mathcal{K}}(z)$ is given in the following result, see [12, Proposition 3.3].

Lemma 2.2 *For any given $z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}$, we have*

$$P_{\mathcal{K}}(z) = \max\{0, \eta_1\}u^{(1)} + \max\{0, \eta_2\}u^{(2)},$$

where η_1, η_2 are the spectral values and $u^{(1)}, u^{(2)}$ are the spectral vectors of z , respectively, given by

$$\begin{aligned} \eta_1 &:= z_0 - \|\bar{z}\|, & \eta_2 &:= z_0 + \|\bar{z}\|, \\ u^{(1)} &:= \begin{cases} \frac{1}{2} \begin{pmatrix} 1 \\ -\frac{\bar{z}}{\|\bar{z}\|} \end{pmatrix} & \text{if } \bar{z} \neq 0, \\ \frac{1}{2} \begin{pmatrix} 1 \\ -\bar{w} \end{pmatrix} & \text{if } \bar{z} = 0, \end{cases} & u^{(2)} &:= \begin{cases} \frac{1}{2} \begin{pmatrix} 1 \\ \frac{\bar{z}}{\|\bar{z}\|} \end{pmatrix} & \text{if } \bar{z} \neq 0, \\ \frac{1}{2} \begin{pmatrix} 1 \\ \bar{w} \end{pmatrix} & \text{if } \bar{z} = 0, \end{cases} \end{aligned}$$

where \bar{w} is any vector in \mathbb{R}^{n-1} with $\|\bar{w}\| = 1$.

It is well-known that the projection mapping onto an arbitrary closed convex set is non-expansive and hence is Lipschitz continuous. When the set is the second-order cone \mathcal{K} , a stronger smoothness property can be shown, see [5, Proposition 4.3], [7, Proposition 7], or [13, Proposition 4.5].

Lemma 2.3 *The projection mapping $P_{\mathcal{K}}$ is strongly semismooth.*

We next characterize the points at which the projection mapping $P_{\mathcal{K}}$ is differentiable.

Lemma 2.4 *The projection mapping $P_{\mathcal{K}}$ is differentiable at a point $z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}$ if and only if $z_0 \neq \pm\|\bar{z}\|$ holds. In fact, the projection mapping is continuously differentiable at every z such that $z_0 \neq \pm\|\bar{z}\|$.*

Proof. The statement can be derived directly from the representation of $P_{\mathcal{K}}(z)$ given in Lemma 2.2. Alternatively, it can be derived as a special case of more general results stated in [7], see, in particular, Propositions 4 and 5 in that reference. \square

We next calculate the Jacobian of the projection mapping $P_{\mathcal{K}}$ at a point where it is differentiable. The proof is not difficult and therefore omitted.

Lemma 2.5 *The Jacobian of $P_{\mathcal{K}}$ at a point $z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}$ with $z_0 \neq \pm\|\bar{z}\|$ is given by*

$$P'_{\mathcal{K}}(z) = \begin{cases} 0, & \text{if } z_0 < -\|\bar{z}\|, \\ I_n, & \text{if } z_0 > +\|\bar{z}\|, \\ \frac{1}{2} \begin{pmatrix} 1 & \bar{w}^T \\ \bar{w} & H \end{pmatrix}, & \text{if } -\|\bar{z}\| < z_0 < +\|\bar{z}\|, \end{cases}$$

where

$$\bar{w} := \frac{\bar{z}}{\|\bar{z}\|}, \quad H := \left(1 + \frac{z_0}{\|\bar{z}\|}\right)I_{n-1} - \frac{z_0}{\|\bar{z}\|}\bar{w}\bar{w}^T.$$

(Note that the denominator is automatically nonzero in this case.)

Based on the above results, we give in the next lemma an expression for the elements of the B-subdifferential $\partial_B P_{\mathcal{K}}(z)$ at an arbitrary point z . A similar representation of the elements of the Clarke generalized Jacobian $\partial P_{\mathcal{K}}(z)$ is given in [13, Proposition 4.8] (see also [19, Lemma 14] and [7, Lemma 4]), and hence we omit the proof of the lemma. Note that we deal with the smaller set $\partial_B P_{\mathcal{K}}(z)$ here, since this will simplify our subsequent analysis to give sufficient conditions for the nonsingularity of all elements in $\partial_B P_{\mathcal{K}}(z)$. In fact, the nonsingularity of all elements of the B-subdifferential usually holds under weaker assumptions than the nonsingularity of all elements of the corresponding Clarke generalized Jacobian.

Lemma 2.6 *Given a general point $z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}$, each element $V \in \partial_B P_{\mathcal{K}}(z)$ has the following representation:*

- (a) *If $z_0 \neq \pm\|\bar{z}\|$, then $P_{\mathcal{K}}$ is continuously differentiable at z and $V = P'_{\mathcal{K}}(z)$ with the Jacobian $P'_{\mathcal{K}}(z)$ given in Lemma 2.5.*
- (b) *If $\bar{z} \neq 0$ and $z_0 = +\|\bar{z}\|$, then*

$$V \in \left\{ I_n, \frac{1}{2} \begin{pmatrix} 1 & \bar{w}^T \\ \bar{w} & H \end{pmatrix} \right\},$$

where $\bar{w} := \frac{\bar{z}}{\|\bar{z}\|}$ and $H := 2I_{n-1} - \bar{w}\bar{w}^T$.

- (c) *If $\bar{z} \neq 0$ and $z_0 = -\|\bar{z}\|$, then*

$$V \in \left\{ 0, \frac{1}{2} \begin{pmatrix} 1 & \bar{w}^T \\ \bar{w} & H \end{pmatrix} \right\},$$

where $\bar{w} := \frac{\bar{z}}{\|\bar{z}\|}$ and $H := \bar{w}\bar{w}^T$.

(d) If $\bar{z} = 0$ and $z_0 = 0$, then either $V = 0$ or $V = I_n$ or V belongs to the set

$$\left\{ \frac{1}{2} \begin{pmatrix} 1 & \bar{w}^T \\ \bar{w} & H \end{pmatrix} \mid H = (1 + \rho)I_{n-1} - \rho\bar{w}\bar{w}^T \text{ for some } |\rho| \leq 1 \text{ and } \|\bar{w}\| = 1 \right\}.$$

We can summarize Lemma 2.6 as follows: Any element $V \in \partial_B P_{\mathcal{K}}(z)$ is equal to

$$V = 0 \quad \text{or} \quad V = I_n \quad \text{or} \quad V = \frac{1}{2} \begin{pmatrix} 1 & \bar{w}^T \\ \bar{w} & H \end{pmatrix} \quad (3)$$

for some vector $\bar{w} \in \mathbb{R}^{n-1}$ with $\|\bar{w}\| = 1$ and some matrix $H \in \mathbb{R}^{(n-1) \times (n-1)}$ of the form $H = (1 + \rho)I_{n-1} - \rho\bar{w}\bar{w}^T$ with some scalar $\rho \in \mathbb{R}$ satisfying $|\rho| \leq 1$. Specifically, in cases (a)–(c), we have $\bar{w} = \bar{z}/\|\bar{z}\|$, whereas in case (d), \bar{w} can be any vector of length one. Moreover, we have $\rho = z_0/\|\bar{z}\|$ in case (a), $\rho = 1$ in case (b), $\rho = -1$ in case (c), whereas there is no further specification of ρ in case (d) (here the two simple cases $V = 0$ and $V = I_n$ are always excluded).

Remark 2.7 The special cases of $n = 1$ and $n = 2$ are not excluded in the above and the subsequent arguments. In fact, when $n = 1$, any element $V \in \partial_B P_{\mathcal{K}}(z)$ is either of the 1×1 matrices $V = (0)$ and $V = (1)$. When $n = 2$, it is one of the following 2×2 matrices:

$$V = 0 \quad \text{or} \quad V = I_2 \quad \text{or} \quad V = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \quad \text{or} \quad V = \frac{1}{2} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}.$$

The eigenvalues and eigenvectors of any matrix $V \in \partial_B P_{\mathcal{K}}(z)$ can be given explicitly, as shown in the following result.

Lemma 2.8 *Let $z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}$ and $V \in \partial_B P_{\mathcal{K}}(z)$. Assume that $V \notin \{0, I_n\}$ so that V has the third representation in (3) with $H = (1 + \rho)I_{n-1} - \rho\bar{w}\bar{w}^T$ for some scalar $\rho \in [-1, +1]$ and some vector $\bar{w} \in \mathbb{R}^{n-1}$ satisfying $\|\bar{w}\| = 1$. Then V has the two single eigenvalues $\eta = 0$ and $\eta = 1$ as well as the eigenvalue $\eta = \frac{1}{2}(1 + \rho)$ with multiplicity $n - 2$ (unless $\rho = \pm 1$, where the multiplicities change in an obvious way). In particular, when $P'_{\mathcal{K}}(z)$ exists, i.e., in case (a) of Lemma 2.6, the multiple eigenvalue is given by $\eta = \frac{1}{2}(1 + \frac{z_0}{\|\bar{z}\|})$. Moreover, the eigenvectors of V are given by*

$$\begin{pmatrix} -1 \\ \bar{w} \end{pmatrix}, \begin{pmatrix} 1 \\ \bar{w} \end{pmatrix}, \text{ and } \begin{pmatrix} 0 \\ \bar{v}_j \end{pmatrix}, \quad j = 1, \dots, n - 2, \quad (4)$$

where $\bar{v}_1, \dots, \bar{v}_{n-2}$ are arbitrary vectors that span the linear subspace $\{\bar{v} \in \mathbb{R}^{n-1} \mid \bar{v}^T \bar{w} = 0\}$.

Proof. By assumption, we have

$$V = \frac{1}{2} \begin{pmatrix} 1 & \bar{w}^T \\ \bar{w} & H \end{pmatrix} \quad \text{with} \quad H = (1 + \rho)I_{n-1} - \rho\bar{w}\bar{w}^T$$

for some $\rho \in [-1, +1]$ and some vector \bar{w} satisfying $\|\bar{w}\| = 1$. Now take an arbitrary vector $\bar{v} \in \mathbb{R}^{n-1}$ orthogonal to \bar{w} , and let $u = (0, \bar{v}^T)^T$. Then an elementary calculation shows that $Vu = \eta u$ holds for $\eta = \frac{1}{2}(1 + \rho)$. Hence this η is an eigenvalue of V with multiplicity $n - 2$ since we can choose $n - 2$ linearly independent vectors $\bar{v} \in \mathbb{R}^{n-1}$ such that $\bar{v}^T \bar{w} = 0$. On the other hand, if $\eta = 0$, it is easy to see that $Vu = \eta u$ holds with $u = (-1, \bar{w}^T)^T$, whereas for $\eta = 1$ we have $Vu = \eta u$ by taking $u = (1, \bar{w}^T)^T$. The multiple eigenvalue of $P'_\mathcal{K}(z)$ (in the differentiable case) can be checked directly from the formula given in Lemma 2.5. This completes the proof. \square

Note that Lemma 2.8 particularly implies $\eta \in [0, 1]$ for all eigenvalues η of V . This observation can alternatively be derived from the fact that $P_\mathcal{K}$ is a projection mapping, without referring to the explicit representation of V as given in Lemma 2.6.

We close this section by pointing out an interesting relation between the matrix $V \in \partial_B P_\mathcal{K}(z)$ and the so-called arrow matrix

$$\mathbf{Arw}(z) := \begin{pmatrix} z_0 & \bar{z}^T \\ \bar{z} & z_0 I_{n-1} \end{pmatrix} \in \mathbb{R}^{n \times n}$$

associated with $z = (z_0, \bar{z}) \in \mathbb{R} \times \mathbb{R}^{n-1}$, which frequently occurs in the context of interior-point methods and in the analysis of SOCPs, see, e.g., [1]. To this end, consider the case where $P_\mathcal{K}$ is differentiable at z , excluding the two trivial cases where $P'_\mathcal{K}(z) = 0$ or $P'_\mathcal{K}(z) = I_n$, cf. Lemma 2.5. Then by Lemma 2.8, the eigenvalues of the matrix $V = P'_\mathcal{K}(z)$ are given by $\eta = 0$, $\eta = 1$, and $\eta = \frac{1}{2}(1 + \frac{z_0}{\|\bar{z}\|})$ with multiplicity $n - 2$, and the corresponding eigenvectors are given by

$$\begin{pmatrix} -1 \\ \frac{\bar{z}}{\|\bar{z}\|} \end{pmatrix}, \begin{pmatrix} 1 \\ \frac{\bar{z}}{\|\bar{z}\|} \end{pmatrix}, \text{ and } \begin{pmatrix} 0 \\ \bar{v}_j \end{pmatrix}, \quad j = 1, \dots, n - 2, \quad (5)$$

where $\bar{v}_1, \dots, \bar{v}_{n-2}$ comprise an orthogonal basis of the linear subspace $\{\bar{v} \in \mathbb{R}^{n-1} \mid \bar{v}^T \bar{z} = 0\}$. However, an elementary calculation shows that these are also the eigenvectors of the arrow matrix $\mathbf{Arw}(z)$, with corresponding single eigenvalues $\hat{\eta}_1 = z_0 - \|\bar{z}\|$, $\hat{\eta}_2 = z_0 + \|\bar{z}\|$ and the multiple eigenvalues $\hat{\eta}_i = z_0$, $i = 3, \dots, n$. Therefore, although the eigenvalues of $V = P'_\mathcal{K}(z)$ and $\mathbf{Arw}(z)$ are different, both matrices have the same set of eigenvectors.

3 Second-Order Cone Programs

In this section, we consider the SOCP

$$\min f(x) \quad \text{s.t.} \quad Ax = b, \quad x \in \mathcal{K},$$

where $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a twice continuously differentiable function, $A \in \mathbb{R}^{m \times n}$ is a given matrix, $b \in \mathbb{R}^m$ is a given vector, and $\mathcal{K} = \mathcal{K}_1 \times \dots \times \mathcal{K}_r$ is the Cartesian product of second-order cones $\mathcal{K}_i \subseteq \mathbb{R}^{n_i}$ with $n_1 + \dots + n_r = n$. The vector x and the matrix A are partitioned

as $x = (x_1, \dots, x_r)$ and $A = (A_1, \dots, A_r)$, respectively, where $x_i = (x_{i0}, \bar{x}_i) \in \mathbb{R} \times \mathbb{R}^{n_i-1}$ and $A_i \in \mathbb{R}^{m \times n_i}$, $i = 1, \dots, r$. Thus the linear constraints $Ax = b$ can alternatively be written as $\sum_{i=1}^r A_i x_i = b$. Although the objective function f is supposed to be nonlinear in general, we will particularly discuss the linear case as well.

Under certain conditions like convexity of f and a Slater-type constraint qualification [4], solving the SOCP is equivalent to solving the corresponding KKT conditions, which can be written as follows:

$$\begin{aligned} \nabla f(x) - A^T \mu - \lambda &= 0, \\ Ax &= b, \\ x_i \in \mathcal{K}_i, \lambda_i \in \mathcal{K}_i, x_i^T \lambda_i &= 0, \quad i = 1, \dots, r. \end{aligned}$$

Using Lemma 2.1, it follows that these KKT conditions are equivalent to the system of equations $M(z) = 0$, where $M : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^n \rightarrow \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^n$ is defined by

$$M(z) := M(x, \mu, \lambda) := \begin{pmatrix} \nabla f(x) - A^T \mu - \lambda \\ Ax - b \\ x_1 - P_{\mathcal{K}_1}(x_1 - \lambda_1) \\ \vdots \\ x_r - P_{\mathcal{K}_r}(x_r - \lambda_r) \end{pmatrix}. \quad (6)$$

Then we can apply the nonsmooth Newton method [22, 23, 20]

$$z^{k+1} := z^k - W_k^{-1} M(z^k), \quad W_k \in \partial_B M(z^k), \quad k = 0, 1, 2, \dots, \quad (7)$$

to the system of equations $M(z) = 0$ in order to solve the SOCP or, at least, the corresponding KKT conditions. Our aim is to show fast local convergence of this iterative method. In view of the results in [23, 22], we have to guarantee that, on the one hand, the mapping M , though not differentiable everywhere, is still sufficiently ‘smooth’, and, on the other hand, it satisfies a local nonsingularity condition under suitable assumptions.

The required smoothness property of M is summarized in the following result.

Theorem 3.1 *The mapping M defined by (6) is semismooth. Moreover, if the Hessian $\nabla^2 f$ is locally Lipschitz continuous, then the mapping M is strongly semismooth.*

Proof. Note that a continuously differentiable mapping is semismooth. Moreover, if the Jacobian of a differentiable mapping is locally Lipschitz continuous, then this mapping is strongly semismooth. Now Lemma 2.3 and the fact that a given mapping is (strongly) semismooth if and only if all component functions are (strongly) semismooth yield the desired result. \square

Our next step is to provide suitable conditions which guarantee the nonsingularity of all elements of the B-subdifferential of M at a KKT point. This requires some more work, and we begin with the following general result.

Proposition 3.2 *Let $H \in \mathbb{R}^{n \times n}$ be symmetric, and $A \in \mathbb{R}^{m \times n}$. Let $V^a, V^b \in \mathbb{R}^{n \times n}$ be two symmetric positive semidefinite matrices such that their sum $V^a + V^b$ is positive definite and V^a and V^b have a common basis of eigenvectors, so that there exist an orthogonal matrix $Q \in \mathbb{R}^{n \times n}$ and diagonal matrices $D^a = \text{diag}(a_1, \dots, a_n)$ and $D^b = \text{diag}(b_1, \dots, b_n)$ satisfying $V^a = QD^aQ^T, V^b = QD^bQ^T$ as well as $a_j \geq 0, b_j \geq 0$ and $a_j + b_j > 0$ for all $j = 1, \dots, n$. Let the index set $\{1, \dots, n\}$ be partitioned as $\{1, \dots, n\} = \alpha \cup \beta \cup \gamma$, where*

$$\begin{aligned}\alpha &:= \{j \mid a_j > 0, b_j = 0\}, \\ \beta &:= \{j \mid a_j > 0, b_j > 0\}, \\ \gamma &:= \{j \mid a_j = 0, b_j > 0\},\end{aligned}$$

and let Q_α, Q_β , and Q_γ denote the submatrices of Q consisting of the columns from Q corresponding to the index sets α, β , and γ , respectively. Let us also partition the diagonal matrices D^a and D^b into $D^a = \text{diag}(D_\alpha^a, D_\beta^a, D_\gamma^a)$ and $D^b = \text{diag}(D_\alpha^b, D_\beta^b, D_\gamma^b)$, respectively, and let

$$D_\beta := (D_\beta^b)^{-1}D_\beta^a. \quad (8)$$

Assume that the following two conditions hold:

(a) The matrix $(AQ_\beta, AQ_\gamma) \in \mathbb{R}^{m \times (|\beta| + |\gamma|)}$ has full row rank.

(b) The matrix

$$\begin{pmatrix} Q_\beta^T H Q_\beta + D_\beta & Q_\beta^T H Q_\gamma \\ Q_\gamma^T H Q_\beta & Q_\gamma^T H Q_\gamma \end{pmatrix} \in \mathbb{R}^{(|\beta| + |\gamma|) \times (|\beta| + |\gamma|)}$$

is positive definite on the subspace $\mathcal{V} := \left\{ \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} \in \mathbb{R}^{|\beta| + |\gamma|} \mid (AQ_\beta, AQ_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0 \right\}$.

Then the matrix

$$W := \begin{pmatrix} H & -A^T & -I_n \\ A & 0 & 0 \\ V^a & 0 & V^b \end{pmatrix}$$

is nonsingular. In particular, when $H = 0$, the matrix W is nonsingular if the following condition holds together with (a):

(c) The matrix AQ_γ has full column rank.

Proof. An elementary calculation shows that the matrix W is nonsingular if and only if the matrix

$$W' := \begin{pmatrix} Q^T H Q & -(AQ)^T & -I_n \\ AQ & 0 & 0 \\ D^a & 0 & D^b \end{pmatrix}$$

is nonsingular. Taking into account the definition of the three index sets α, β, γ , we obtain

$$D^a = \text{diag}(D_\alpha^a, D_\beta^a, D_\gamma^a) = \text{diag}(D_\alpha^a, D_\beta^a, 0),$$

$$D^b = \text{diag}(D_\alpha^b, D_\beta^b, D_\gamma^b) = \text{diag}(0, D_\beta^b, D_\gamma^b).$$

Using this structure and premultiplying the matrix W' by

$$\begin{pmatrix} I_n & & \\ & I_m & \\ & & D \end{pmatrix} \quad \text{with} \quad D := \text{diag}((D_\alpha^a)^{-1}, (D_\beta^a)^{-1}, I_{|\gamma|}),$$

we see that the matrix W' is nonsingular if and only if

$$W'' := \begin{pmatrix} Q^T H Q & -(A Q)^T & -I_n \\ A Q & 0 & 0 \\ \tilde{D}^a & 0 & \tilde{D}^b \end{pmatrix}$$

is nonsingular, where \tilde{D}^a and \tilde{D}^b are diagonal matrices given by

$$\tilde{D}^a := \text{diag}(I_{|\alpha|}, I_{|\beta|}, 0) \quad \text{and} \quad \tilde{D}^b := \text{diag}(0, D_\beta^{-1}, D_\gamma^b).$$

Note that the matrix D_β defined by (8) is a positive definite diagonal matrix. It then follows that the matrix W'' is a block upper triangular matrix with its lower right block D_γ^b being a nonsingular diagonal matrix. Therefore the matrix W'' is nonsingular if and only if its upper left block

$$\tilde{W} := \begin{pmatrix} Q^T H Q & -(A Q)^T & -I_\alpha & -I_\beta \\ A Q & 0 & 0 & 0 \\ I_\alpha^T & 0 & 0 & 0 \\ I_\beta^T & 0 & 0 & D_\beta^{-1} \end{pmatrix} \quad (9)$$

is nonsingular, where I_α, I_β denote the matrices in $\mathbb{R}^{n \times |\alpha|}, \mathbb{R}^{n \times |\beta|}$ consisting of all columns of the identity matrix corresponding to the index sets $i \in \alpha, i \in \beta$, respectively. (Note the difference between I_α, I_β and the square matrices $I_{|\alpha|}, I_{|\beta|}$.) In other words, the matrix W is nonsingular if and only if \tilde{W} is nonsingular.

In order to show the nonsingularity of \tilde{W} , let $\tilde{W}y = 0$ for a suitably partitioned vector $y = (d, p, q_\alpha, q_\beta)^T \in \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^{|\alpha|} \times \mathbb{R}^{|\beta|}$. We will see that $y = 0$ under assumptions (a) and (b). Using (9), we may write $\tilde{W}y = 0$ as

$$Q^T H Q d - Q^T A^T p - \begin{pmatrix} q_\alpha \\ q_\beta \\ 0 \end{pmatrix} = 0, \quad (10)$$

$$A Q d = 0, \quad (11)$$

$$d_\alpha = 0, \quad (12)$$

$$d_\beta + D_\beta^{-1} q_\beta = 0. \quad (13)$$

Premultiplying (10) by d^T and taking into account (11) and (12), we obtain

$$\begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix}^T (Q_\beta, Q_\gamma)^T H (Q_\beta, Q_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} - d_\beta^T q_\beta = 0,$$

which along with (13) yields

$$\begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix}^T \begin{pmatrix} Q_\beta^T H Q_\beta + D_\beta & Q_\beta^T H Q_\gamma \\ Q_\gamma^T H Q_\beta & Q_\gamma^T H Q_\gamma \end{pmatrix} \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0.$$

On the other hand, from (11) and (12), we have

$$(A Q_\beta, A Q_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0. \quad (14)$$

Then, by assumption (b), we obtain $d_\beta = 0$ and $d_\gamma = 0$, which together with (13) implies $q_\beta = 0$. Now it follows from (10) that

$$-Q_\alpha^T A^T p - q_\alpha = 0 \quad (15)$$

and

$$- \begin{pmatrix} Q_\beta^T A^T \\ Q_\gamma^T A^T \end{pmatrix} p = 0. \quad (16)$$

By assumption (a), (16) yields $p = 0$, which in turn implies $q_\alpha = 0$ from (15). Consequently, we have $y = 0$. This shows \tilde{W} , and hence W , is nonsingular.

When $H = 0$, we obtain from (10)–(13)

$$d_\beta^T D_\beta d_\beta = -d_\beta^T q_\beta = 0.$$

Since D_β is positive definite, this implies $d_\beta = 0$. Then by assumption (c), it follows from (14) that $d_\gamma = 0$. The rest of the proof goes in the same manner as above. \square

The two central assumptions (a) and (b) of Proposition 3.2 can also be formulated in a different way: Using some elementary calculations, it is not difficult to see that assumption (a) is equivalent to

(a') The matrix $(Q^T A^T, I_\alpha) \in \mathbb{R}^{n \times (m+|\alpha|)}$ has full column rank;

whereas assumption (b) is equivalent to

(b') $H + Q_\beta D_\beta Q_\beta^T$ is positive definite on the subspace $\mathcal{S} := \{v \in \mathbb{R}^n \mid Av = 0, Q_\alpha^T v = 0\}$.

At this point, let us examine how stringent the conditions in Proposition 3.2 are. In view of the particular structure of the matrix \tilde{W} given in (9), we notice from condition (a') that (a) is also a necessary condition for the nonsingularity of the matrix W in Proposition 3.2. Furthermore, note that condition (b) obviously implies that the following implication holds:

$$\left. \begin{aligned} \begin{pmatrix} Q_\beta^T H Q_\beta + D_\beta & Q_\beta^T H Q_\gamma \\ Q_\gamma^T H Q_\beta & Q_\gamma^T H Q_\gamma \end{pmatrix} \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} &= 0, \\ (A Q_\beta, A Q_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} &= 0 \end{aligned} \right\} \implies \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0. \quad (17)$$

We claim that this (slightly weaker and, for positive semidefinite H , actually equivalent) condition is also necessary for the nonsingularity of W . To see this, suppose there is a vector $(d_\beta, d_\gamma) \neq (0, 0)$ such that

$$\begin{pmatrix} Q_\beta^T H Q_\beta + D_\beta & Q_\beta^T H Q_\gamma \\ Q_\gamma^T H Q_\beta & Q_\gamma^T H Q_\gamma \end{pmatrix} \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0 \quad \text{and} \quad (A Q_\beta, A Q_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0,$$

and define

$$d_\alpha := 0, \quad p := 0, \quad q_\alpha := Q_\alpha^T H Q_\beta d_\beta + Q_\alpha^T H Q_\gamma d_\gamma, \quad q_\beta := -D_\beta d_\beta.$$

A simple calculation then shows that we have $\tilde{W}y = 0$ for the nonzero vector $y := (d^T, p^T, q_\alpha^T, q_\beta^T)^T$. Hence \tilde{W} is singular, implying that W itself is singular.

Thus, condition (a) and the slightly relaxed version (17) of condition (b) are both necessary for the nonsingularity of the matrix W in Proposition 3.2. This fact suggests that it is not easy to weaken these conditions. We stress this point here because in the following we will directly translate the conditions of Proposition 3.2 to the case of second-order cone programs. These translations may look rather complicated, but they result quite naturally from Proposition 3.2, and the above discussion shows that it is, in the above sense, not easy to relax the assumptions.

Now let us go back to the mapping M defined by (6). In order to apply Proposition 3.2 to the (generalized) Jacobian of the mapping M at a KKT point, we first introduce some more notation:

$$\begin{aligned} \text{int}\mathcal{K}_i &:= \{x_i \mid x_{i0} > \|\bar{x}_i\|\} && \text{denotes the interior of } \mathcal{K}_i, \\ \text{bd}\mathcal{K}_i &:= \{x_i \mid x_{i0} = \|\bar{x}_i\|\} && \text{denotes the boundary of } \mathcal{K}_i, \text{ and} \\ \text{bd}^+\mathcal{K}_i &:= \text{bd}\mathcal{K}_i \setminus \{0\} && \text{is the boundary of } \mathcal{K}_i \text{ excluding the origin.} \end{aligned}$$

We also call a KKT point $z^* = (x^*, \mu^*, \lambda^*)$ of the SOCP *strictly complementary* if $x_i^* + \lambda_i^* \in \text{int}\mathcal{K}_i$ holds for all block components $i = 1, \dots, r$. This notation enables us to restate the following result from [1].

Lemma 3.3 *Let $z^* = (x^*, \mu^*, \lambda^*)$ be a KKT point of the SOCP. Then precisely one of the following six cases holds for each block pair (x_i^*, λ_i^*) , $i = 1, \dots, r$:*

x_i^*	λ_i^*	SC
$x_i^* \in \text{int}\mathcal{K}_i$	$\lambda_i^* = 0$	<i>yes</i>
$x_i^* = 0$	$\lambda_i^* \in \text{int}\mathcal{K}_i$	<i>yes</i>
$x_i^* \in \text{bd}^+\mathcal{K}_i$	$\lambda_i^* \in \text{bd}^+\mathcal{K}_i$	<i>yes</i>
$x_i^* \in \text{bd}^+\mathcal{K}_i$	$\lambda_i^* = 0$	<i>no</i>
$x_i^* = 0$	$\lambda_i^* \in \text{bd}^+\mathcal{K}_i$	<i>no</i>
$x_i^* = 0$	$\lambda_i^* = 0$	<i>no</i>

The last column in the table indicates whether or not strict complementarity (SC) holds.

We also need the following simple result which, in particular, shows that the projection mapping $P_{\mathcal{K}_i}$ involved in the definition of the mapping M is continuously differentiable at $s_i := x_i^* - \lambda_i^*$ for any block component i satisfying strict complementarity.

Lemma 3.4 *Let $z^* = (x^*, \mu^*, \lambda^*)$ be a KKT point of the SOCP. Then the following statements hold for each block pair (x_i^*, λ_i^*) :*

- (a) *If $x_i^* \in \text{int}\mathcal{K}_i$ and $\lambda_i^* = 0$, then $P_{\mathcal{K}_i}$ is continuously differentiable at $s_i := x_i^* - \lambda_i^*$ with $P'_{\mathcal{K}_i}(s_i) = I_{n_i}$.*
- (b) *If $x_i^* = 0$ and $\lambda_i^* \in \text{int}\mathcal{K}_i$, then $P_{\mathcal{K}_i}$ is continuously differentiable at $s_i := x_i^* - \lambda_i^*$ with $P'_{\mathcal{K}_i}(s_i) = 0$.*
- (c) *If $x_i^* \in \text{bd}^+\mathcal{K}_i$ and $\lambda_i^* \in \text{bd}^+\mathcal{K}_i$, then $P_{\mathcal{K}_i}$ is continuously differentiable at $s_i := x_i^* - \lambda_i^*$ with $P'_{\mathcal{K}_i}(s_i) = \frac{1}{2} \begin{pmatrix} 1 & \bar{w}_i^T \\ \bar{w}_i & H_i \end{pmatrix}$, where $\bar{w}_i = \frac{\bar{s}_i}{\|\bar{s}_i\|}$ and $H_i = (1 + \frac{s_{i0}}{\|\bar{s}_i\|})I_{n_i-1} - \frac{s_{i0}}{\|\bar{s}_i\|}\bar{w}_i\bar{w}_i^T$.*

Proof. Parts (a) and (b) immediately follow from Lemma 2.5. To prove part (c), write $x_i^* = (x_{i0}^*, \bar{x}_i^*)$, $\lambda_i^* = (\lambda_{i0}^*, \bar{\lambda}_i^*)$, and $s_i = (s_{i0}, \bar{s}_i) := x_i^* - \lambda_i^* = (x_{i0}^* - \lambda_{i0}^*, \bar{x}_i^* - \bar{\lambda}_i^*)$. Since $x_i^* \neq 0$ and $\lambda_i^* \neq 0$, we see from [1, Lemma 15] that there is a constant $\rho > 0$ such that $\lambda_{i0}^* = \rho x_{i0}^*$ and $\bar{\lambda}_i^* = -\rho \bar{x}_i^*$, implying $s_{i0} = (1 - \rho)x_{i0}^*$ and $\|\bar{s}_i\| = (1 + \rho)\|\bar{x}_i^*\|$. Since $x_{i0}^* = \|\bar{x}_i^*\| \neq 0$ by assumption, we have $s_{i0} = \frac{1-\rho}{1+\rho}\|\bar{s}_i\|$. Hence we obtain $s_{i0} = \|\bar{s}_i\| - \frac{2\rho}{1+\rho}\|\bar{s}_i\| < \|\bar{s}_i\|$ and $s_{i0} = \frac{2}{1+\rho}\|\bar{s}_i\| - \|\bar{s}_i\| > -\|\bar{s}_i\|$. The desired result then follows from Lemma 2.5. \square

We are now almost in a position to apply Proposition 3.2 to the Jacobian of the mapping M at a KKT point $z^* = (x^*, \mu^*, \lambda^*)$ provided that this KKT point satisfies strict complementarity. This strict complementarity assumption will be removed later, but for the moment it is quite convenient to assume this condition. For example, it then follows from Lemma 3.3 that the three index sets

$$\begin{aligned} J_I &:= \{i \mid x_i^* \in \text{int}\mathcal{K}_i, \lambda_i^* = 0\}, \\ J_B &:= \{i \mid x_i^* \in \text{bd}^+\mathcal{K}_i, \lambda_i^* \in \text{bd}^+\mathcal{K}_i\}, \\ J_0 &:= \{i \mid x_i^* = 0, \lambda_i^* \in \text{int}\mathcal{K}_i\} \end{aligned} \tag{18}$$

form a partition of the block indices $i = 1, \dots, r$. Here, the subscripts I, B and 0 indicate whether the block component x_i^* belongs to the interior of the cone \mathcal{K}_i , or x_i^* belongs to the boundary of \mathcal{K}_i (excluding the zero vector), or x_i^* is the zero vector.

Let $V_i := P'_{\mathcal{K}_i}(x_i^* - \lambda_i^*)$. Then Lemma 3.4 implies that

$$V_i = I_{n_i} \quad \forall i \in J_I \quad \text{and} \quad V_i = 0 \quad \forall i \in J_0. \tag{19}$$

To get a similar representation for indices $i \in J_B$, we need the spectral decompositions $V_i = Q_i D_i Q_i^T$ of the matrices V_i . Since strict complementarity holds, it follows from

Lemmas 2.8 and 3.4 that each V_i has precisely one eigenvalue equal to zero and precisely one eigenvalue equal to one, whereas all other eigenvalues are strictly between zero and one. Without loss of generality, we can therefore assume that the eigenvalues of V_i are ordered in such a way that

$$D_i = \text{diag}(0, \eta_i, \dots, \eta_i, 1) \quad \forall i \in J_B, \quad (20)$$

where η_i denotes the multiple eigenvalue that lies in the open interval $(0, 1)$. Correspondingly we also partition the orthogonal matrices Q_i as

$$Q_i = (q_i, \hat{Q}_i, q'_i) \quad \forall i \in J_B, \quad (21)$$

where $q_i \in \mathbb{R}^{n_i}$ denotes the first column of Q_i , $q'_i \in \mathbb{R}^{n_i}$ is the last column of Q_i , and $\hat{Q}_i \in \mathbb{R}^{n_i \times (n_i - 2)}$ contains the remaining $n_i - 2$ middle columns of Q_i . We also use the following partitionings of the matrices Q_i :

$$Q_i = (q_i, \bar{Q}_i) = (\tilde{Q}_i, q'_i) \quad \forall i \in J_B, \quad (22)$$

where, again, $q_i \in \mathbb{R}^{n_i}$ and $q'_i \in \mathbb{R}^{n_i}$ are the first and the last columns of Q_i , respectively, and $\bar{Q}_i \in \mathbb{R}^{n_i \times (n_i - 1)}$ and $\tilde{Q}_i \in \mathbb{R}^{n_i \times (n_i - 1)}$ contain the remaining $n_i - 1$ columns of Q_i . It is worth noticing that, by (5), the vectors q_i and q'_i are actually given by

$$q_i = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 \\ \frac{\bar{x}_i^* - \bar{\lambda}_i^*}{\|\bar{x}_i^* - \bar{\lambda}_i^*\|} \end{pmatrix} \quad \text{and} \quad q'_i = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \frac{\bar{x}_i^* - \bar{\lambda}_i^*}{\|\bar{x}_i^* - \bar{\lambda}_i^*\|} \end{pmatrix},$$

where $1/\sqrt{2}$ is the normalizing coefficient. Also, by Lemma 2.8, the eigenvalue η_i in (20) is given by

$$\eta_i = \frac{1}{2} \left(1 + \frac{x_{i0}^* - \lambda_{i0}^*}{\|\bar{x}_i^* - \bar{\lambda}_i^*\|} \right). \quad (23)$$

(From [1, Lemma 15], we may easily deduce $\bar{x}_i^* - \bar{\lambda}_i^* \neq 0$ whenever $x_i^{*T} \lambda_i^* = 0$, $x_i^* \in \text{bd}^+ \mathcal{K}_i$, $\lambda_i^* \in \text{bd}^+ \mathcal{K}_i$.)

Consider the matrix D_β defined by (8). In the SOCP under consideration, for each $j \in \beta$, a_j and b_j are given by

$$a_j = \frac{1}{2} \left(1 - \frac{s_{i0}}{\|\bar{s}_i\|} \right), \quad b_j = \frac{1}{2} \left(1 + \frac{s_{i0}}{\|\bar{s}_i\|} \right)$$

with $s_i := x_i^* - \lambda_i^*$ corresponding to some index i belonging to J_B (cf. the proof of Theorem 3.5 below). For any such pair (x_i^*, λ_i^*) , $i \in J_B$, we have

$$x_{i0}^* = \|\bar{x}_i^*\|, \quad \lambda_{i0}^* = \|\bar{\lambda}_i^*\|$$

and

$$x_i^* = \rho_i R_i \lambda_i^*,$$

where $\rho_i = x_{i0}^*/\lambda_{i0}^*$ and $R_i = \begin{pmatrix} 1 & 0 \\ 0 & -I_{n_i-1} \end{pmatrix}$, see [1, Lemma 15]. Hence we have

$$s_i = (\rho_i R_i - I_{n_i})\lambda_i^* = - \begin{pmatrix} (1 - \rho_i)\lambda_{i0}^* \\ (1 + \rho_i)\bar{\lambda}_i^* \end{pmatrix},$$

which implies $s_{i0}/\|\bar{s}_i\| = (1 - \rho_i)/(1 + \rho_i)$. Therefore we obtain

$$a_j = \frac{\rho_i}{1 + \rho_i}, \quad b_j = \frac{1}{1 + \rho_i}, \quad \frac{a_j}{b_j} = \rho_i \left(= \frac{x_{i0}^*}{\lambda_{i0}^*} \right).$$

This indicates that $D_\beta = (D_\beta^b)^{-1}D_\beta^a$ is a block diagonal matrix with block components of the form $\rho_i I$, where ρ_i and the size of the identity matrix I vary with blocks. The matrix D_β contains the curvature information of the second-order cone at a boundary surface and $\rho_i = x_{i0}^*/\lambda_{i0}^*$ corresponds to the quantity that appears in the second-order condition given by Bonnans and Ramírez [3, eq.(43)]. In fact, we may regard the conditions given in this paper as a dual counterpart of those given in [3], since the problem studied in the present paper corresponds to the primal problem and that of [3] corresponds to the dual problem in the sense of [1].

We are now able to prove the following nonsingularity result under the assumption that the given KKT point satisfies strict complementarity. In the theorem, the index sets β and γ will be implicitly defined through AQ_β and AQ_γ , respectively, since it is more convenient than stating their definitions explicitly. Indeed, as described in the proof of the theorem, β is defined as the index set consisting of the middle $(n_i - 2)$ components of each block component $i \in J_B$, while γ consists of all components of each block component $i \in J_I$ and the last component of each block component $i \in J_B$. Incidentally, the index set α , which does not appear in the conditions of the theorem, consists of all the remaining components, that is, all components of each block component $i \in J_0$ and the first component of each block component $i \in J_B$.

Theorem 3.5 *Let $z^* = (x^*, \mu^*, \lambda^*)$ be a strictly complementary KKT point of the SOCP (2), let $H := \nabla^2 f(x^*)$ with block components $H_{ij} := \nabla_{x_i x_j}^2 f(x^*)$, and let the (block) index sets J_I, J_B, J_0 be defined by (18). Let*

$$AQ_\beta := \left((A_i \hat{Q}_i)_{i \in J_B} \right) \in \mathbb{R}^{m \times |\beta|}, \quad AQ_\gamma := \left((A_i)_{i \in J_I}, (A_i q'_i)_{i \in J_B} \right) \in \mathbb{R}^{m \times |\gamma|},$$

$$|\beta| := \sum_{i \in J_B} (n_i - 2) = \sum_{i \in J_B} n_i - 2|J_B|, \quad |\gamma| := \sum_{i \in J_I} n_i + |J_B|,$$

and

$$D_\beta := \text{diag} \left((\rho_i I_{n_i-2})_{i \in J_B} \right) \in \mathbb{R}^{|\beta| \times |\beta|} \quad \text{with} \quad \rho_i := \frac{x_{i0}^*}{\lambda_{i0}^*} \quad (i \in J_B).$$

Then the Jacobian $M'(z^*)$ exists and is nonsingular if the following conditions hold:

- (a) The matrix $(AQ_\beta, AQ_\gamma) \in \mathbb{R}^{m \times (|\beta| + |\gamma|)}$ has full row rank.

(b) The matrix

$$\begin{pmatrix} C_1 + D_\beta & C_2 \\ C_2^T & C_3 \end{pmatrix} \in \mathbb{R}^{(|\beta|+|\gamma|) \times (|\beta|+|\gamma|)}$$

is positive definite on the subspace $\mathcal{V} := \left\{ \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} \in \mathbb{R}^{|\beta|+|\gamma|} \mid (AQ_\beta, AQ_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0 \right\}$,
where

$$\begin{aligned} C_1 &:= \left((\hat{Q}_i^T H_{ij} \hat{Q}_j)_{i,j \in J_B} \right) \in \mathbb{R}^{|\beta| \times |\beta|}, \\ C_2 &:= \left((\hat{Q}_i^T H_{ij})_{i \in J_B, j \in J_I}, (\hat{Q}_i^T H_{ij} q'_j)_{i \in J_B, j \in J_B} \right) \in \mathbb{R}^{|\beta| \times |\gamma|}, \\ C_3 &:= \begin{pmatrix} (H_{ij})_{i \in J_I, j \in J_I} & (H_{ij} q'_j)_{i \in J_I, j \in J_B} \\ (q_i^T H_{ij})_{i \in J_B, j \in J_I} & (q_i^T H_{ij} q'_j)_{i \in J_B, j \in J_B} \end{pmatrix} \in \mathbb{R}^{|\gamma| \times |\gamma|}. \end{aligned}$$

For the linear SOCP (1), the assertion holds with condition (b) replaced by the following condition:

(c) The matrix $AQ_\gamma \in \mathbb{R}^{m \times |\gamma|}$ has full column rank.

Proof. The existence of the Jacobian $M'(z^*)$ follows immediately from the assumed strict complementarity of the given KKT point together with Lemma 3.4. A simple calculation shows that

$$M'(z^*) = \begin{pmatrix} H & -A^T & -I_n \\ A & 0 & 0 \\ I_n - V & 0 & V \end{pmatrix},$$

where V is the block diagonal matrix $\text{diag}(V_1, \dots, V_r)$ with $V_i := P'_{\mathcal{K}_i}(x_i^* - \lambda_i^*)$. Therefore, taking into account the fact that all eigenvalues of the matrix V belong to the interval $[0, 1]$ by Lemma 2.8, we are able to apply Proposition 3.2 (with $V^a := I_n - V$ and $V^b := V$) as soon as we identify the index sets $\alpha, \beta, \gamma \subseteq \{1, \dots, n\}$ and the structure of the matrices Q and D from that result. To this end, we consider each block index i separately. Note that, since the matrix V has n columns $j = 1, \dots, n$, and since we only have r block indices $i = 1, \dots, r$, each block index i generally consists of several components j .

For each $i \in J_I$, we have $V_i = I_{n_i}$ (see (19)) and, therefore, $Q_i = I_{n_i}$ and $D_i = I_{n_i}$. Hence all components j from the block components $i \in J_I$ belong to the index set γ .

On the other hand, for each $i \in J_0$, we have $V_i = 0$ (see (19)), and this corresponds to $Q_i = I_{n_i}$ and $D_i = 0$. Hence all components j from the block components $i \in J_0$ belong to the index set α .

Finally, let $i \in J_B$. Then $V_i = Q_i D_i Q_i^T$ with $D_i = \text{diag}(0, \eta_i, \dots, \eta_i, 1)$, where $\eta_i \in (0, 1)$ is given by (23), and $Q_i = (q_i, \hat{Q}_i, q'_i)$. Hence the first component for each block index $i \in J_B$ is an element of the index set α , the last component for each block index $i \in J_B$ belongs to the index set γ , and all the remaining middle components belong to the index set β .

Taking into account that $Q = \text{diag}(Q_1, \dots, Q_r)$ and $D = \text{diag}(D_1, \dots, D_r)$ with Q_i, D_i as specified above, and using the partitioning

$$\begin{pmatrix} (H_{ij})_{i \in J_I, j \in J_I} & (H_{ij})_{i \in J_I, j \in J_B} & (H_{ij})_{i \in J_I, j \in J_0} \\ (H_{ij})_{i \in J_B, j \in J_I} & (H_{ij})_{i \in J_B, j \in J_B} & (H_{ij})_{i \in J_B, j \in J_0} \\ (H_{ij})_{i \in J_0, j \in J_I} & (H_{ij})_{i \in J_0, j \in J_B} & (H_{ij})_{i \in J_0, j \in J_0} \end{pmatrix}$$

of the Hessian $H = \nabla^2 f(x^*)$, it follows immediately from the above observations that conditions (a), (b), and (c) correspond precisely to conditions (a), (b), and (c), respectively, in Proposition 3.2. \square

The following simple example illustrates the conditions in the above theorem.

Example 3.6 Consider the nonlinear SOCP

$$\begin{aligned} \min \quad & \frac{1}{2}x_1^2 + \frac{1}{2}(x_2 - 2)^2 - \frac{\varepsilon}{2}x_3^2 \\ \text{s.t.} \quad & x \in \mathcal{K}^3, \end{aligned}$$

where \mathcal{K}^3 denotes the second-order cone in \mathbb{R}^3 and ε is a scalar parameter. This problem contains only one second-order cone constraint. (Here, unlike the rest of this section, x_i denotes the i th (scalar) component of the vector x .) Note that the objective function is nonconvex for any $\varepsilon > 0$. It is easy to see that the solution of this problem is given by $x^* = (1, 1, 0)^T \in \text{bd}^+ \mathcal{K}^3$ together with the multiplier vector $\lambda^* = (1, -1, 0)^T \in \text{bd}^+ \mathcal{K}^3$, which satisfies strict complementarity. Furthermore, we have

$$V = P'_{\mathcal{K}^3}(x^* - \lambda^*) = QDQ^T,$$

where $D = \text{diag}(0, \frac{1}{2}, 1)$ and

$$Q = (q, \hat{Q}, q') = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \end{pmatrix}.$$

Since there is no equality constraint, condition (a) in Theorem 3.5 is automatically satisfied. Moreover, by direct calculation, we have $C_1 = -\varepsilon$, $C_2 = 0$, $C_3 = 1$, $D_\beta = 1$, and hence

$$\begin{pmatrix} C_1 + D_\beta & C_2 \\ C_2^T & C_3 \end{pmatrix} = \begin{pmatrix} -\varepsilon + 1 & 0 \\ 0 & 1 \end{pmatrix},$$

for which condition (b) holds as long as $\varepsilon < 1$, since $\mathcal{V} = \mathbb{R}^2$. This example shows that condition (b) may be secured with the aid of the curvature term D_β even if the Hessian of the objective function fails to be positive definite in itself. \diamond

We now want to extend Theorem 3.5 to the case where strict complementarity is violated. Let $z^* = (x^*, \mu^*, \lambda^*)$ be an arbitrary KKT point of the SOCP, and let J_I, J_B, J_0 denote the index sets defined by (18). In view of Lemma 3.3, in addition to these sets, we also need to consider the three index sets

$$\begin{aligned} J_{B0} &:= \{i \mid x_i^* \in \text{bd}^+ \mathcal{K}_i, \lambda_i^* = 0\}, \\ J_{0B} &:= \{i \mid x_i^* = 0, \lambda_i^* \in \text{bd}^+ \mathcal{K}_i\}, \\ J_{00} &:= \{i \mid x_i^* = 0, \lambda_i^* = 0\}, \end{aligned} \tag{24}$$

which correspond to the block indices where strict complementarity is violated. Note that these index sets have double subscripts; the first (resp. second) subscript indicates whether x_i^* (resp. λ_i^*) is on the boundary of \mathcal{K}_i (excluding zero) or equal to the zero vector. Note that the index sets J_{B0}, J_{0B} , as well as J_B are empty whenever $n_i = 1$ since these cases simply do not exist in the one-dimensional setting.

The following lemma summarizes the structure of the matrices $V_i \in \partial_B P_{\mathcal{K}_i}(x_i^* - \lambda_i^*)$ for $i \in J_{B0} \cup J_{0B} \cup J_{00}$, in which we use the same notations as those defined in (20)–(22) for $i \in J_B$. Hence this lemma is the counterpart of Lemma 3.4 in the general case.

Lemma 3.7 *Let $i \in J_{B0} \cup J_{0B} \cup J_{00}$ and $V_i \in \partial_B P_{\mathcal{K}_i}(x_i^* - \lambda_i^*)$. Then the following statements hold:*

- (a) *If $i \in J_{B0}$, then we have either $V_i = I_{n_i}$ or $V_i = Q_i D_i Q_i^T$ with $D_i = \text{diag}(0, 1, \dots, 1)$ and $Q_i = (q_i, \bar{Q}_i)$.*
- (b) *If $i \in J_{0B}$, then we have either $V_i = 0$ or $V_i = Q_i D_i Q_i^T$ with $D_i = \text{diag}(0, \dots, 0, 1)$ and $Q_i = (\tilde{Q}_i, q'_i)$.*
- (c) *If $i \in J_{00}$, then we have $V_i = I_{n_i}$ or $V_i = 0$ or $V_i = Q_i D_i Q_i^T$ with D_i and Q_i given by $D_i = \text{diag}(0, \eta_i, \dots, \eta_i, 1)$ for some $\eta_i \in (0, 1)$ and $Q_i = (q_i, \hat{Q}_i, q'_i)$, or by $D_i = \text{diag}(0, 1, \dots, 1)$ and $Q_i = (q_i, \bar{Q}_i)$, or by $D_i = \text{diag}(0, \dots, 0, 1)$ and $Q_i = (\tilde{Q}_i, q'_i)$.*

Proof. First let $i \in J_{B0}$. Then $s_i := x_i^* - \lambda_i^* = x_i^* \in \text{bd}^+ \mathcal{K}_i$. Therefore, if we write $s_i = (s_{i0}, \bar{s}_i)$, it follows that $s_{i0} = \|\bar{s}_i\|$ and $\bar{s}_i \neq 0$. Statement (a) then follows immediately from Lemma 2.6 (b) in combination with Lemma 2.8.

In a similar way, the other two statements can be derived by using Lemma 2.6 (c) and (d), respectively, together with Lemma 2.8 in order to get the eigenvalues. Here the five possible choices in statement (c) depend, in particular, on the value of the scalar ρ in Lemma 2.6 (d) (namely $\rho \in (-1, 1)$, $\rho = 1$, and $\rho = -1$). \square

Lemma 3.7 enables us to generalize Theorem 3.5 to the case where strict complementarity does not hold. Note that we use the spectral decompositions $V_i = Q_i D_i Q_i^T$ and the associated partitionings (20)–(22) for all $i \in J_B$, as well as those specified in Lemma 3.7 for all indices $i \in J_{B0} \cup J_{0B} \cup J_{00}$. Moreover, we will employ implicit definitions of the index sets β and γ as in Theorem 3.5; see the remark preceding Theorem 3.5.

Theorem 3.8 Let $z^* = (x^*, \mu^*, \lambda^*)$ be a (not necessarily strictly complementary) KKT point of the SOCP (2), let $H := \nabla^2 f(x^*)$ with block components $H_{ij} := \nabla_{x_i x_j}^2 f(x^*)$, and let the (block) index sets $J_I, J_B, J_0, J_{B0}, J_{0B}, J_{00}$ be defined by (18) and (24). Then all matrices $W \in \partial_B M(z^*)$ are nonsingular if, for any partitioning $J_{B0} = J_{B0}^1 \cup J_{B0}^2$, any partitioning $J_{0B} = J_{0B}^1 \cup J_{0B}^2$, and any partitioning $J_{00} = J_{00}^1 \cup J_{00}^2 \cup J_{00}^3 \cup J_{00}^4 \cup J_{00}^5$ such that $J_{00}^3 = J_{00}^4 = \emptyset$ when $n_i \leq 2$ and $J_{00}^5 = \emptyset$ when $n_i = 1$, the following two conditions (a) and (b) hold with

$$\begin{aligned} AQ_\beta &:= \left((A_i \hat{Q}_i)_{i \in J_B \cup J_{00}^3} \right) \in \mathbb{R}^{m \times |\beta|}, \\ AQ_\gamma &:= \left((A_i)_{i \in J_I \cup J_{B0}^1 \cup J_{00}^1}, (A_i q'_i)_{i \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5}, (A_i \bar{Q}_i)_{i \in J_{B0}^2 \cup J_{00}^4} \right) \in \mathbb{R}^{m \times |\gamma|}, \\ |\beta| &:= \sum_{i \in J_B \cup J_{00}^3} (n_i - 2), \\ |\gamma| &:= \sum_{i \in J_I \cup J_{B0}^1 \cup J_{00}^1} n_i + |J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5| + \sum_{i \in J_{B0}^2 \cup J_{00}^4} (n_i - 1), \\ D_\beta &:= \text{diag} \left((\rho_i I_{n_i - 2})_{i \in J_B \cup J_{00}^3} \right) \in \mathbb{R}^{|\beta| \times |\beta|} \\ &\quad \text{with } \rho_i = \frac{x_{i0}^*}{\lambda_{i0}^*} \text{ (} i \in J_B \text{), } \rho_i > 0 \text{ (} i \in J_{00}^3 \text{):} \end{aligned}$$

(a) The matrix $(AQ_\beta, AQ_\gamma) \in \mathbb{R}^{m \times (|\beta| + |\gamma|)}$ has full row rank.

(b) The matrix

$$\begin{pmatrix} C_1 + D_\beta & C_2 \\ C_2^T & C_3 \end{pmatrix} \in \mathbb{R}^{(|\beta| + |\gamma|) \times (|\beta| + |\gamma|)}$$

is positive definite on the subspace $\mathcal{V} := \left\{ \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} \in \mathbb{R}^{|\beta| + |\gamma|} \mid (AQ_\beta, AQ_\gamma) \begin{pmatrix} d_\beta \\ d_\gamma \end{pmatrix} = 0 \right\}$, where

$$\begin{aligned} C_1 &:= \left((\hat{Q}_i^T H_{ij} \hat{Q}_j)_{i, j \in J_B \cup J_{00}^3} \right) \in \mathbb{R}^{|\beta| \times |\beta|}, \\ C_2 &:= (C_2^1, C_2^2, C_2^3) \in \mathbb{R}^{|\beta| \times |\gamma|}, \\ C_3 &:= \begin{pmatrix} C_3^{11} & C_3^{12} & C_3^{13} \\ (C_3^{12})^T & C_3^{22} & C_3^{23} \\ (C_3^{13})^T & (C_3^{23})^T & C_3^{33} \end{pmatrix} \in \mathbb{R}^{|\gamma| \times |\gamma|} \end{aligned}$$

with the submatrices

$$\begin{aligned} C_2^1 &:= \left((\hat{Q}_i^T H_{ij})_{i \in J_B \cup J_{00}^3, j \in J_I \cup J_{B0}^1 \cup J_{00}^1} \right), \\ C_2^2 &:= \left((\hat{Q}_i^T H_{ij} q'_j)_{i \in J_B \cup J_{00}^3, j \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5} \right), \\ C_2^3 &:= \left((\hat{Q}_i^T H_{ij} \bar{Q}_j)_{i \in J_B \cup J_{00}^3, j \in J_{B0}^2 \cup J_{00}^4} \right) \end{aligned}$$

and

$$\begin{aligned}
C_3^{11} &:= \left((H_{ij})_{i \in J_I \cup J_{B0}^1 \cup J_{00}^1, j \in J_I \cup J_{B0}^1 \cup J_{00}^1} \right), \\
C_3^{12} &:= \left((H_{ij} q'_j)_{i \in J_I \cup J_{B0}^1 \cup J_{00}^1, j \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5} \right), \\
C_3^{13} &:= \left((H_{ij} \bar{Q}_j)_{i \in J_I \cup J_{B0}^1 \cup J_{00}^1, j \in J_{B0}^2 \cup J_{00}^4} \right), \\
C_3^{22} &:= \left((q_i'^T H_{ij} q'_j)_{i \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5, j \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5} \right), \\
C_3^{23} &:= \left((q_i'^T H_{ij} \bar{Q}_j)_{i \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5, j \in J_{B0}^2 \cup J_{00}^4} \right), \\
C_3^{33} &:= \left((\bar{Q}_i^T H_{ij} \bar{Q}_j)_{i \in J_{B0}^2 \cup J_{00}^4, j \in J_{B0}^2 \cup J_{00}^4} \right).
\end{aligned}$$

For the linear SOCP (1), the assertion holds with condition (b) replaced by the following condition:

(c) The matrix $AQ_\gamma \in \mathbb{R}^{m \times |\gamma|}$ has full column rank.

Proof. Choose $W \in \partial_B M(z^*)$ arbitrarily. Then a simple calculation shows that

$$W = \begin{pmatrix} H & -A^T & -I_n \\ A & 0 & 0 \\ I_n - V & 0 & V \end{pmatrix}$$

for a suitable block diagonal matrix $V = \text{diag}(V_1, \dots, V_r)$ with $V_i \in \partial_B P_{\mathcal{K}_i}(x_i^* - \lambda_i^*)$. In principle, the proof is similar to the one of Theorem 3.5: We want to apply Proposition 3.2 (with $V^a := I - V$ and $V^b := V$). To this end, we (once again) have to identify the index sets α, β, γ (and the corresponding matrices Q, D). The statement itself then follows immediately from Proposition 3.2.

Before identifying the index sets α, β, γ , we stress once more that we only have r block indices i , whereas there are $n \geq r$ columns j in the matrix V . Hence each block index i generally consists of several components j . If, for example, the block index i consists of the columns $j = 5, 6, 7, 8$, we call $j = 5$ the first component of the block index i , $j = 8$ the last component of i , and $j = 6, 7$ the middle components of i .

The situation here is, unfortunately, much more complicated than in the proof of Theorem 3.5, since the index sets α, β, γ may depend on the particular element W chosen from the B-subdifferential $\partial_B M(z^*)$. To identify these index sets, we need to take a closer look especially at the index sets J_{B0}, J_{0B} , and J_{00} . In view of Lemma 3.7, we further partition these index sets into

$$\begin{aligned}
J_{B0} &= J_{B0}^1 \cup J_{B0}^2, \\
J_{0B} &= J_{0B}^1 \cup J_{0B}^2, \\
J_{00} &= J_{00}^1 \cup J_{00}^2 \cup J_{00}^3 \cup J_{00}^4 \cup J_{00}^5
\end{aligned}$$

with

$$\begin{aligned} J_{B0}^1 &:= \{i \mid V_i = I_{n_i}\}, & J_{B0}^2 &:= J_{B0} \setminus J_{B0}^1, \\ J_{0B}^1 &:= \{i \mid V_i = 0\}, & J_{0B}^2 &:= J_{0B} \setminus J_{0B}^1, \end{aligned}$$

and

$$\begin{aligned} J_{00}^1 &:= \{i \mid V_i = I_{n_i}\}, \\ J_{00}^2 &:= \{i \mid V_i = 0\}, \\ J_{00}^3 &:= \{i \mid V_i = Q_i D_i Q_i^T \text{ with } D_i \text{ and } Q_i \text{ given by (20) and (21), respectively}\}, \\ J_{00}^4 &:= \{i \mid V_i = Q_i D_i Q_i^T \text{ with } D_i = \text{diag}(0, 1, \dots, 1) \text{ and } Q_i = (q_i, \bar{Q}_i)\}, \\ J_{00}^5 &:= \{i \mid V_i = Q_i D_i Q_i^T \text{ with } D_i = \text{diag}(0, \dots, 0, 1) \text{ and } Q_i = (\tilde{Q}_i, q'_i)\}. \end{aligned}$$

Using these definitions and Lemmas 3.4 and 3.7, we see that the following indices j belong to the index set α in Proposition 3.2:

- All components j of the block indices $i \in J_0 \cup J_{0B}^1 \cup J_{00}^2$, with $Q_i = I_{n_i}$ being the corresponding orthogonal matrix.
- The first components j of the block indices $i \in J_B \cup J_{B0}^2 \cup J_{00}^3 \cup J_{00}^4$, with q_i being the first column of the corresponding orthogonal matrix Q_i .
- The first $n_i - 1$ components j of the block indices $i \in J_{0B}^2 \cup J_{00}^5$, with \tilde{Q}_i consisting of the first $n_i - 1$ columns of the corresponding orthogonal matrix Q_i .

We next consider the index set β in Proposition 3.2. In view of Lemmas 3.4 and 3.7, the following indices j belong to this set:

- All middle components j of the block indices $i \in J_B \cup J_{00}^3$, with \hat{Q}_i consisting of the middle $n_i - 2$ columns of the corresponding orthogonal matrix Q_i .

Using Lemmas 3.4 and 3.7 again, we finally see that the following indices j belong to the index set γ in Proposition 3.2:

- All components j of the block indices $i \in J_I \cup J_{B0}^1 \cup J_{00}^1$. The corresponding orthogonal matrix is $Q_i = I_{n_i}$.
- The last components j of the block indices $i \in J_B \cup J_{0B}^2 \cup J_{00}^3 \cup J_{00}^5$, with q'_i being the last column of the corresponding orthogonal matrix Q_i .
- The last $n_i - 1$ components j of the block indices $i \in J_{B0}^2 \cup J_{00}^4$, with \bar{Q}_i consisting of the last $n_i - 1$ columns of the corresponding orthogonal matrix Q_i .

The theorem then follows from Proposition 3.2 in a way similar to the proof of Theorem 3.5. \square

Note that the second-order condition (b) of Theorem 3.8 holds, in particular, if $H = \nabla^2 f(x^*)$ is positive definite. This follows immediately from its derivation via Proposition 3.2 (see also condition (b') given after the proof of Proposition 3.2).

Further note that, in the case of a strictly complementary KKT point, Theorem 3.8 reduces to Theorem 3.5. It may be worth noticing that, for interior-point methods of the linear SOCP, we cannot expect to have a result corresponding to Theorem 3.8, since the Jacobian matrices arising in that context are singular whenever the strict complementarity fails to hold.

The next example, which is an instance of the linear SOCP and will also be used in the numerical experiments (Example 4.3) in Section 4, illustrates how the conditions in Theorem 3.8 can be verified when the strict complementarity is not satisfied.

Example 3.9 Consider the problem of minimizing the maximum distance to N points b_i ($i = 1, \dots, N$) in the Euclidean space \mathbb{R}^ν :

$$\min_{t \in \mathbb{R}, y \in \mathbb{R}^\nu} t \quad \text{s.t.} \quad \|y - b_i\| \leq t, \quad i = 1, \dots, N.$$

By translating the axes if necessary, we assume without loss of generality that $b_1 = 0$. Then this problem can be rewritten as

$$\begin{aligned} & \text{minimize} && t \\ & \text{subject to} && x_1 - x_i = \begin{pmatrix} 0 \\ b_i \end{pmatrix}, \quad i = 2, \dots, N, \\ & && x_1 := \begin{pmatrix} t \\ y \end{pmatrix} \in \mathcal{K}^{\nu+1}, \quad x_i \in \mathcal{K}^{\nu+1}, \quad i = 2, \dots, N, \end{aligned}$$

where $\mathcal{K}^{\nu+1}$ denotes the second-order cone in $\mathbb{R}^{\nu+1}$. This is a linear SOCP of the standard form

$$\min f(x) \quad \text{s.t.} \quad Ax = b, \quad x \in \mathcal{K},$$

with the objective function $f(x) := c^T x$, the variables

$$x := (x_1^T, \dots, x_N^T)^T \in \mathbb{R}^n, \quad n := (\nu + 1)N,$$

and the data

$$\begin{aligned} c &:= (1, 0, \dots, 0)^T \in \mathbb{R}^n, \\ b &:= (0, b_2^T, 0, b_3^T, \dots, 0, b_N^T)^T \in \mathbb{R}^{(\nu+1)(N-1)}, \\ A &:= \begin{pmatrix} I_{\nu+1} & -I_{\nu+1} & & & 0 \\ I_{\nu+1} & & -I_{\nu+1} & & \\ \vdots & & & \ddots & \\ I_{\nu+1} & 0 & & & -I_{\nu+1} \end{pmatrix} \in \mathbb{R}^{(\nu+1)(N-1) \times n}, \\ \mathcal{K} &:= \underbrace{\mathcal{K}^{\nu+1} \times \dots \times \mathcal{K}^{\nu+1}}_{N\text{-times}} \subseteq \mathbb{R}^n. \end{aligned}$$

To be more specific, let us consider the particular instance with $\nu = 2$, $N = 3$, and $b_2 = (4, 0)^T$, $b_3 = (4, 4)^T$. The solution of this problem is given by $x_1^* = (t^*, y^{*T})^T = (2\sqrt{2}, 2, 2)^T$, $x_2^* = (2\sqrt{2}, -2, 2)^T$ and $x_3^* = (2\sqrt{2}, -2, -2)^T$, i.e.,

$$x^* = (x_1^{*T}, x_2^{*T}, x_3^{*T})^T = (2\sqrt{2}, 2, 2, 2\sqrt{2}, -2, 2, 2\sqrt{2}, -2, -2)^T.$$

An elementary calculation then shows that the corresponding optimal multipliers are given by $\mu^* = (0, 0, 0, \frac{1}{2}, \frac{1}{2\sqrt{2}}, \frac{1}{2\sqrt{2}})^T$ and

$$\lambda^* = (\lambda_1^{*T}, \lambda_2^{*T}, \lambda_3^{*T})^T = (\frac{1}{2}, \frac{-1}{2\sqrt{2}}, \frac{-1}{2\sqrt{2}}, 0, 0, 0, \frac{1}{2}, \frac{1}{2\sqrt{2}}, \frac{1}{2\sqrt{2}})^T.$$

Looking at the pair (x^*, λ^*) , we find that the strict complementarity is violated in the second block component.

To examine the conditions of Theorem 3.8, we need the orthogonal matrices Q_i , $i = 1, 2, 3$, that appear in the spectral decompositions $V_i = Q_i D_i Q_i^T$ of $V_i \in \partial_B P_{\mathcal{K}_i}(x_i^* - \lambda_i^*)$. For the first block component $i = 1$, we have $x_1^* = (2\sqrt{2}, 2, 2)^T$, $\lambda_1^* = (\frac{1}{2}, \frac{-1}{2\sqrt{2}}, \frac{-1}{2\sqrt{2}})^T$, which yield $s_1 := x_1^* - \lambda_1^* = (\frac{4\sqrt{2}-1}{2}, \frac{4\sqrt{2}+1}{2\sqrt{2}}, \frac{4\sqrt{2}+1}{2\sqrt{2}})^T$ and $\bar{w}_1 := \bar{s}_1 / \|\bar{s}_1\| = (\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})^T$. In view of Lemma 2.8, the orthogonal matrix Q_1 associated with the first block is obtained by normalizing the vectors in (4) as

$$Q_1 = (q_1 \hat{Q}_1 q'_1) = (q_1 \hat{q}_1 q'_1) = \begin{pmatrix} \frac{-1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{-1}{\sqrt{2}} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{\sqrt{2}} & \frac{1}{2} \end{pmatrix}. \quad (25)$$

Here, notice that we denote the middle component of Q_1 by $\hat{Q}_1 = \hat{q}_1$, since it consists of only one column. Similarly, for the other two block components, we have

$$Q_2 = (q_2 \hat{q}_2 q'_2) = \begin{pmatrix} \frac{-1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{-1}{2} & \frac{1}{\sqrt{2}} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{\sqrt{2}} & \frac{1}{2} \end{pmatrix}, \quad Q_3 = (q_3 \hat{q}_3 q'_3) = \begin{pmatrix} \frac{-1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ \frac{-1}{2} & \frac{-1}{\sqrt{2}} & \frac{1}{2} \\ \frac{-1}{2} & \frac{1}{\sqrt{2}} & \frac{-1}{2} \end{pmatrix}. \quad (26)$$

Now let us verify that the conditions in Theorem 3.8 (for the linear SOCP) hold for this particular example. Note that, at the complementary pair (x^*, λ^*) , we have $J_I = J_0 = J_{0B} = J_{00} = \emptyset$, $J_B = \{1, 3\}$ and $J_{B_0} = \{2\}$. In particular, there exist only two possible partitionings of the index set $J_{B_0} = J_{B_0}^1 \cup J_{B_0}^2$, i.e., (i) $J_{B_0}^1 = \{2\}$, $J_{B_0}^2 = \emptyset$ and (ii) $J_{B_0}^1 = \emptyset$, $J_{B_0}^2 = \{2\}$.

Case (i). Noticing that the size of each block is $n_i = \nu + 1 = 3$, we have $|\beta| = \sum_{i \in J_B} (n_i - 2) = 2$, $|\gamma| = \sum_{i \in J_{B_0}^1} n_i + |J_B| = 3 + 2 = 5$, and

$$AQ_\beta = (A_1 \hat{q}_1 \ A_3 \hat{q}_3) \in \mathbb{R}^{6 \times 2}, \quad AQ_\gamma = (A_2 \ A_1 q'_1 \ A_3 q'_3) \in \mathbb{R}^{6 \times 5}. \quad (27)$$

Since the matrix A is partitioned as $A = (A_1 \ A_2 \ A_3)$ with

$$A_1 = \begin{pmatrix} I \\ I \end{pmatrix}, \quad A_2 = \begin{pmatrix} -I \\ 0 \end{pmatrix}, \quad A_3 = \begin{pmatrix} 0 \\ -I \end{pmatrix} \in \mathbb{R}^{6 \times 3}, \quad (28)$$

we have from (27)

$$AQ_\beta = \begin{pmatrix} \hat{q}_1 & 0 \\ \hat{q}_1 & -\hat{q}_3 \end{pmatrix} \in \mathbb{R}^{6 \times 2}, \quad AQ_\gamma = \begin{pmatrix} -I & q'_1 & 0 \\ 0 & q'_1 & -q'_3 \end{pmatrix} \in \mathbb{R}^{6 \times 5},$$

where $\hat{q}_1, q'_1, \hat{q}_3, q'_3$ are given by (25) and (26). Notice that $\hat{q}_1 = \hat{q}_3$. Then it is not difficult to conclude that the condition (a) holds, since the matrix

$$(\hat{q}_1 \ q'_1 \ q'_3) = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{2} \\ \frac{-1}{\sqrt{2}} & \frac{1}{2} & \frac{-1}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{-1}{2} \end{pmatrix} \in \mathbb{R}^{3 \times 3}$$

is nonsingular. Moreover, since vectors q'_1 and q'_3 are linearly independent, the condition (c) holds.

Case (ii). We have $|\beta| = \sum_{i \in J_B} (n_i - 2) = 2$, $|\gamma| = |J_B| + \sum_{i \in J_{B_0}^2} (n_i - 1) = 2 + 2 = 4$, and

$$AQ_\beta = (A_1 \hat{q}_1 \ A_3 \hat{q}_3) \in \mathbb{R}^{6 \times 2}, \quad AQ_\gamma = (A_1 q'_1 \ A_3 q'_3 \ A_2 \bar{Q}_2) = (A_1 q'_1 \ A_3 q'_3 \ A_2 \hat{q}_2 \ A_2 q'_2) \in \mathbb{R}^{6 \times 4}.$$

By (28), (25) and (26), we have

$$\begin{aligned} (AQ_\beta \ AQ_\gamma) &= \begin{pmatrix} \hat{q}_1 & 0 & q'_1 & 0 & -\hat{q}_2 & -q'_2 \\ \hat{q}_1 & -\hat{q}_3 & q'_1 & -q'_3 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{2}} & 0 & 0 & \frac{-1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & 0 & \frac{1}{2} & 0 & \frac{-1}{\sqrt{2}} & \frac{1}{2} \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{2} & 0 & \frac{-1}{\sqrt{2}} & \frac{-1}{2} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 & 0 \\ \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} & 0 & 0 \end{pmatrix}. \end{aligned}$$

By elementary calculation, it is easy to check that this 6×6 matrix is nonsingular, from which both conditions (a) and (c) immediately follow.

The above arguments suggest that, by virtue of the special structure of the matrix A , there is a good chance that the conditions in Theorem 3.8 hold in many instances of this application of SOCP. \diamond

Using Theorems 3.1 and 3.8 along with [22], we get the following result.

Theorem 3.10 *Let $z^* = (x^*, \mu^*, \lambda^*)$ be a (not necessarily strictly complementary) KKT point of the SOCP (1), and suppose that the assumptions of Theorem 3.8 hold at this KKT point. Then the nonsmooth Newton method (7) applied to the system of equations $M(z) = 0$ is locally superlinearly convergent. If, in addition, f has a locally Lipschitz continuous Hessian, then it is locally quadratically convergent.*

To conclude this section, let us consider the special case where \mathcal{K} is the nonnegative orthant \mathbb{R}_+^r , i.e., $n_i = 1$ for all $i = 1, \dots, r$, and see how the conditions in Theorem 3.8 can be interpreted in this case. First notice that $x_i, \lambda_i \in \mathbb{R}$ and $A_i \in \mathbb{R}^m$ for all i . Moreover, at a KKT point $z^* = (x^*, \mu^*, \lambda^*)$ of the problem, there are only three cases among the six cases shown in Lemma 3.3, that is, the index set $\{1, 2, \dots, r\}$ can be partitioned into the following three subsets:

$$\begin{aligned} J_I &:= \{i \mid x_i^* > 0, \lambda_i^* = 0\}, \\ J_0 &:= \{i \mid x_i^* = 0, \lambda_i^* > 0\}, \\ J_{00} &:= \{i \mid x_i^* = 0, \lambda_i^* = 0\}. \end{aligned}$$

Accordingly we have $J_B = J_{B0} = J_{0B} = \emptyset$, which particularly implies that the (implicitly defined) index set β in Theorem 3.8 is empty. Therefore, the statement of Theorem 3.8 can be phrased as follows: All matrices $W \in \partial_B M(z^*)$ are nonsingular if, for any subset $J_{00}^1 \subseteq J_{00}$, the following conditions (a) and (b) hold with

$$\gamma = J_I \cup J_{00}^1, \quad A_\gamma = \left((A_i)_{i \in \gamma} \right) \in \mathbb{R}^{m \times |\gamma|} :$$

- (a) The matrix A_γ has full row rank.
- (b) The matrix $\nabla_{\gamma\gamma}^2 f(x^*)$ is positive definite on the subspace $\{d_\gamma \in \mathbb{R}^{|\gamma|} \mid A_\gamma d_\gamma = 0\}$, where $\nabla_{\gamma\gamma}^2 f(x^*)$ is the submatrix of $\nabla^2 f(x^*)$ with components $\frac{\partial^2 f(x^*)}{\partial x_i \partial x_j}$ ($i \in \gamma, j \in \gamma$).

When the problem is a linear program, the condition (b) can be replaced by

- (c) The matrix A_γ has full column rank.

By taking a closer look, we see that the above conditions can be replaced by the following simpler conditions, where $\bar{J}_I := J_I \cup J_{00} = \{i \mid \lambda_i^* = 0\} \supseteq J_I = \{i \mid x_i^* > 0\}$:

- (a*) The matrix A_{J_I} has full row rank.
- (b*) The matrix $\nabla_{\bar{J}_I \bar{J}_I}^2 f(x^*)$ is positive definite on the subspace $\{d_{\bar{J}_I} \in \mathbb{R}^{|\bar{J}_I|} \mid A_{\bar{J}_I} d_{\bar{J}_I} = 0\}$.
- (c*) The matrix $A_{\bar{J}_I}$ has full column rank.

Condition (a*) ensures the uniqueness of the Lagrange multiplier vector λ^* . Condition (b*) is a second-order sufficient condition for optimality, which ensures the local uniqueness of the primal solution x^* . In the linear case, (a*) implies $m \leq |J_I|$, while (c*) implies $|\bar{J}_I| \leq m$. However, since $|J_I| \leq |\bar{J}_I|$, we must have $m = |J_I| = |\bar{J}_I|$, and hence J_{00} is empty and A_{J_I} is square and nonsingular. In other words, x^* is a nondegenerate basic solution. Thus the conditions given in Theorem 3.8 reduce to familiar conditions in the special case $\mathcal{K} = \mathbb{R}_+^r$.

k	$\ M(z^k)\ $	x_1^k	x_2^k	x_3^k	$\ \nabla f(x^k) - \lambda^k\ $
0	1.020784e+02	2.000000e+00	2.000000e+00	2.000000e+00	3.464102e+00
1	1.414214e+00	0.000000e+00	2.000000e+00	0.000000e+00	0.000000e+00
2	0.000000e+00	1.000000e+00	1.000000e+00	0.000000e+00	0.000000e+00

Table 1: Numerical results for the nonconvex SOCP of Example 4.1

4 Numerical Examples

In this section, we show some preliminary numerical results with the nonsmooth Newton method tested on linear and nonlinear SOCPs. The main aim of our numerical experiments is to demonstrate the theoretical results established in the previous section by examining the local behaviour of the method, rather than making a comparison with existing solvers. Note that the usage of symbols such as x and x_i in this section is different from the previous sections. However there should be no confusion since the meaning will be clear from the context.

Example 4.1 We first consider the nonconvex SOCP of Example 3.6. Letting $\varepsilon := \frac{1}{2}$ and using the starting point $x^0 := (2, 2, 2)^T$ together with the multipliers $\lambda^0 := (2, 2, 2)^T$, we obtain the results shown in Table 1. Here we have very fast convergence in just two iterations. \diamond

Our next example is taken from [13].

Example 4.2 Consider the following nonlinear (convex) SOCP:

$$\begin{aligned} \min \quad & \exp(x_1 - x_3) + 3(2x_1 - x_2)^4 + \sqrt{1 + (3x_2 + 5x_3)^2} \\ \text{s.t.} \quad & \begin{pmatrix} x_4 \\ x_5 \end{pmatrix} = \begin{pmatrix} 4 & 6 & 3 \\ -1 & 7 & -5 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} -1 \\ 2 \end{pmatrix} \in \mathcal{K}^2, \quad \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \in \mathcal{K}^3, \end{aligned}$$

where \mathcal{K}^r denotes the second-order cone in \mathbb{R}^r . This problem can be written in the standard form

$$\min f(x) \quad \text{s.t.} \quad Ax = b, \quad x \in \mathcal{K}$$

with $f(x) := \exp(x_1 - x_3) + 3(2x_1 - x_2)^4 + \sqrt{1 + (3x_2 + 5x_3)^2}$ and

$$A := \begin{pmatrix} 4 & 6 & 3 & -1 & 0 \\ -1 & 7 & -5 & 0 & -1 \end{pmatrix}, \quad b := \begin{pmatrix} 1 \\ -2 \end{pmatrix}, \quad \mathcal{K} := \mathcal{K}^3 \times \mathcal{K}^2.$$

Table 2 shows a sequence of the first three components of x^k generated by the nonsmooth Newton method with a starting point randomly chosen from the box $[0, 1]^5 \subset \mathbb{R}^5$. We may observe a typical feature of the local quadratic convergence. \diamond

k	$\ M(z^k)\ $	x_1^k	x_2^k	x_3^k	$\ Ax^k - b\ $
0	1.273197e+02	9.501293e-01	2.311385e-01	6.068426e-01	5.663307e+00
1	3.765549e+01	3.019551e-01	-5.312774e-01	1.198684e-01	6.280370e-16
2	3.158146e+01	2.331042e-01	-9.730924e-02	2.171462e-01	1.110223e-15
3	3.259677e+00	1.196822e-01	-9.886805e-02	3.688092e-02	0.000000e+00
4	1.675676e+00	1.973609e-01	-8.539481e-02	2.409751e-01	4.440892e-16
5	3.516159e-01	2.357895e-01	-9.820433e-02	2.153560e-01	1.110223e-16
6	4.875888e-02	2.325429e-01	-7.451132e-02	2.203468e-01	0.000000e+00
7	1.511531e-04	2.324026e-01	-7.308263e-02	2.206131e-01	2.220446e-16
8	7.295537e-10	2.324025e-01	-7.307928e-02	2.206135e-01	1.110223e-16
9	1.102302e-15	2.324025e-01	-7.307928e-02	2.206135e-01	4.440892e-16

Table 2: Numerical results for the nonlinear (convex) SOCP of Example 4.2

k	$\ M(z^k)\ $	x_1^k	x_2^k	$\ Ax^k - b\ $	$\ \phi(x^k, \lambda^k)\ $
0	7.029663e+00	8.121259e-01	9.082626e-01	6.393857e+00	1.769382e+00
1	4.816071e+01	4.094855e+00	2.944570e+00	1.297632e-13	4.816071e+01
2	3.107185e+01	1.971163e+00	1.659028e+00	5.043708e-12	3.107185e+01
3	2.109201e+00	3.278852e+00	9.489322e-01	9.485085e-11	2.109201e+00
4	9.107635e-01	2.232357e+00	1.816440e+00	1.719429e-11	9.107635e-01
5	4.255234e-02	2.032107e+00	1.967839e+00	5.819005e-10	4.255234e-02
6	5.825558e-04	2.000563e+00	1.999989e+00	1.239050e-10	5.825558e-04
7	4.474272e-08	2.000000e+00	2.000000e+00	1.379164e-11	4.474272e-08
8	7.675809e-15	2.000000e+00	2.000000e+00	6.616780e-15	3.890536e-15

Table 3: Numerical results for the linear SOCP of Example 4.3

Example 4.3 We next consider the particular instance of the linear SOCP given in Example 3.9. As shown there, this instance violates the strict complementarity but the conditions in Theorem 3.8 are satisfied. We applied the nonsmooth Newton method to this problem and the results are shown in Table 3, where the function ϕ in the last column is defined by $\phi(x, \lambda) := x - P_{\mathcal{K}}(x - \lambda)$. We observe that the method is just a local one: The residual $\|M(z^k)\|$ increases in the beginning. Fortunately, after a few steps, $\|M(z^k)\|$ starts to decrease, and eventually exhibits nice local quadratic convergence. \diamond

We also applied the nonsmooth Newton method to the three SOCPs in the DIMACS library, see [21]. Due to its local nature, the method sometimes failed to converge depending on the choice of a starting point. Nevertheless, the asymptotic behaviour of the method applied to problem `nb_L1` from the DIMACS collection, as shown in Table 4, indicates that the rate of convergence is at least superlinear for this problem. Whether the non-quadratic convergence has to do with the fact that our assumptions are violated, or it is simply due to the finite precision arithmetic of the computer, is currently not clear to us.

k	$\ M(z^k)\ $	$\ Ax^k - b\ $	$\ \phi(x^k, \lambda^k)\ $
34	2.397717e-03	7.130277e-13	2.397717e-03
35	6.252936e-07	9.029000e-13	6.252936e-07
36	1.470491e-09	5.177835e-13	1.470491e-09
37	4.781069e-12	6.815003e-13	4.732249e-12

Table 4: Numerical results for the linear SOCP nb_L1 from the DIMACS collection

5 Final Remarks

We have investigated the local properties of a semismooth equation reformulation of both the linear and the nonlinear SOCPs. In particular, we have shown nonsingularity results that provide basic conditions for local quadratic convergence of a nonsmooth Newton method. Strict complementarity of a solution is not needed in our nonsingularity results. Apart from these local properties, it is certainly of interest to see how the local Newton method can be globalized in a suitable way. We leave it as a future research topic.

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