Smooth Minimum Distance Estimation and Testing in Conditional Moment Restrictions Models: Uniform in Bandwidth Theory

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Abstract

We propose a new class of estimators for models defined by conditional moment restrictions. Our generic estimator minimizes a distance criterion based on kernel smoothing. We develop a theory that focuses on uniformity in bandwidth. We establish a $\sqrt{n}$-asymptotic representation of our estimator as a process depending on the bandwidth within a wide range including fixed bandwidths and that applies to misspecified models. We also study an efficient version of our estimator. We develop inference procedures based on a distance metric statistic for testing restrictions on parameters and we propose a new bootstrap technique. Our new methods apply to non-smooth problems, are simple to implement, and perform well in small samples.

Keywords: Conditional Moments, Smoothing Methods.
JEL classification: Primary C31; Secondary C13, C14.

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1 Introduction

Many econometric models involve conditional moment restrictions (CMR). Generalized Method of Moments (GMM), as introduced by Hansen (1982), only exploits a finite number of unconditional moment restrictions. Subsequent research has focused on accounting for CMR to gain efficiency. Provided a preliminary consistent estimator, Robinson (1987) and Newey (1993) show how to estimate optimal instruments by nonparametric methods to obtain a two-step efficient estimator. However, as Dominguez and Lobato (2004) point out, in nonlinear models an arbitrary finite number of instruments, and even the optimal ones, may fail to globally identify the parameters of interest, see Dominguez and Lobato (2007) for further examples. The identification issue is crucial in practice: since classical GMM relies on a finite number of unconditional moments, we can never be sure that the chosen ones identify the parameters of interest and the estimator may be inconsistent.

Recent work has then focused on accounting for CMR at the outset. Carrasco and Florens (2000) propose a generalization of efficient GMM to an infinite (countable or uncountable) number of moments. Antoine, Bonnal, and Renault (2007) develop a three-step efficient estimator based on a smoothed euclidean Empirical Likelihood (EL) approach. Donald, Imbens, and Newey (2003), Kitamura, Tripathi, and Ahn (2004), and Smith (2007a,b) focus on smoothed generalized EL methods that provide *one-step* efficient estimators, thus avoiding the need for a preliminary consistent estimator. All these methods rely on a user-chosen parameter, whether it is a regularization parameter, as in Carrasco and Florens (2000), a bandwidth parameter, as in Antoine, Bonnal and Renault (2007), Kitamura, Tripathi and Ahn (2004), and Smith (2007a,b), or the number of series functions, as in Donald, Imbens and Newey (2003). Consistency and efficiency follows when the user-chosen parameter, or its inverse in the latter case, converges to zero as the sample size increases. This parameter however cannot be set set arbitrarily close to zero in empirical applications and its practical choice can be a vexing problem. Dominguez and Lobato (2004) propose the first consistent estimator that does not require a user-chosen parameter, but still exploits all CMR. Efficiency however is not reached using their criterion.

In this work, we propose a new framework for estimation of parameters in models defined by CMR. Our generic estimator optimizes a new minimum distance criterion. Our *smooth minimum distance* (SMD) approach defines a whole class of consistent estimators that depends on a smoothing, or bandwidth, parameter: when this parameter is fixed, our estimator is similar to but different than Dominguez and Lobato's estimator, and our simulations show that it is less variable; when the bandwidth decreases to zero, our estimator is close in spirit, but still different, to other proposals. We develop a theory for SMD estimation and testing that focuses on accounting for the influence of the bandwidth. This feature is crucial since this parameter is usually selected depending on the sample size and the features of the data in applications. It is also key if one wants to determine an optimal data-driven choice, as recently entertained by Carrasco (2007). Though we follow a different route, our work is similar in aim to recent work on heteroscedasticity-autocorrelation robust variance estimators where the focus is to account for the influence of the truncation parameter, see Kiefer and Volgelsang (2005), Sun, Phillips, and Jin (2008), and the references therein. It is also related to recent work on uniform in bandwidth consistency of kernel estimators, see Einmahl and Mason (2005) and the references therein. Specifically, we show uniform in bandwidth consistency and we provide a $\sqrt{n}$-asymptotic representation of the SMD estimator as a process indexed by the bandwidth. To the best of our knowledge, our uniform in bandwidth results are the first of their kind for estimation methods in models defined by CMR and are not available for smoothed EL estimators.

Our asymptotic representation extends to misspecified models. The behavior of GMM under misspecification has recently attracted some attention, see Hall and Inoue (2003), Aguirre-Torres and Dominguez-Toribio (2004), and Dridi, Guay and Renault (2007). Schennach (2007) recently shows that under misspecification the standard EL estimator cannot be $\sqrt{n}$-consistent for a pseudo-true value whenever the functions entering the moment restrictions are unbounded. Little is known on the behavior of estimators based on CMR, but one should fear that such a phenomenon also occurs for smoothed EL estimators. As our results show, the SMD estimator enjoys similar properties whether the model is correct or misspecified.

Our estimator can attain the semiparametric efficiency bound when the bandwidth decreases to zero. The efficient estimator requires neither estimation of conditional expectation of derivatives nor differentiability of the functions entering the moment restrictions. In general, an efficient two-step estimator obtains based on a preliminary SMD estimator, which is consistent irrespective to the bandwidth's choice, and a kernel estimator of the density-weighted conditional variance, which involves a second bandwidth parameter. When the conditional variance is known, as in conditional quantile models, the efficient estimator becomes one-step, as the ones recently proposed by Otsu (2008) and Komunjer and Vuong (2006). We establish the efficiency of our general estimator uniformly within a large range for the two bandwidths involved. From a practical viewpoint, the efficient SMD is easier to implement than the smoothed EL estimator of Kitamura, Tripathi and Ahn (2004). We also show through simulations that it behaves comparatively well in small samples.

Testing restrictions on parameter can be entertained from a distance metric approach based on our SMD criterion. Indeed, twice the difference between the constrained and unconstrained optimized criteria behaves like a likelihood-ratio statistic. When considered as a process, the statistic is a quadratic form in an asymptotically tight Gaussian process. If one neglects the influence of the bandwidth and assumes an efficient estimator, a classical chi-square distribution obtains, but basing the testing procedure on the general distribution should yield more reliable inference. We then extend a simple bootstrap method, recently proposed by Jin, Ying and Wei (2001) and Bose and Chatterjee (2003), to approximate the distribution of our estimator and of our distance metric test statistic. The method perturbs the objective function and does not require resampling observations. To our knowledge, this is the first general bootstrap method proposed to date for inference in nonlinear models defined by CMR. We show that the test and the bootstrap method are valid uniformly in the bandwidth.

We first focus in Section 2 on obtaining general consistency and asymptotic normality results uniformly over a large range of bandwidths including fixed ones. In Section 3, we investigate our distance-metric procedure for testing restrictions on parameters and our proposed bootstrap method for inference. Section 4 focuses on deriving an efficient form of the SMD estimator and shows that our former results extend to the efficient estimator. Section 5 reports the results of a simulation study. Section 6 concludes. Proofs are gathered in Section 7. Two Appendices discuss in detail some of our technical conditions.

2 SMD Estimation

For a matrix A, $\|A\|$ is the usual extension of the Euclidean norm, $\lambda_{\min}(A)$ and $\lambda_{\max}(A)$ denote the smallest and the largest eigenvalue of A when A is square. For a real-valued function $l(\cdot)$, $\mathcal{F}[l](\cdot)$ is its Fourier transform, $\nabla_\theta l(\cdot)$ and $\mathrm{H}_{\theta,\theta} l(\cdot)$ respectively denote the p column vector of first partial derivatives and the $p \times p$ matrix of second derivatives with respect to $\theta \in \mathbb{R}^p$. For a vector-valued function $l(\cdot) \in \mathbb{R}^r$, $\nabla_\theta l(\cdot)$ denotes the $p \times r$ matrix of first derivatives of the entries of $l(\cdot)$ with respect to entries of θ.

2.1 The Estimator

Let $g(Z,\theta) = (g^{(1)}(Z,\theta), ..., g^{(r)}(Z,\theta))'$ be a $r-$vector valued function, $r \geq 1$, with $Z = (Y', X')' \in \mathbb{R}^{d+q}$, $d \geq 1$, $q \geq 1$, and $\theta \in \Theta \subset \mathbb{R}^p$, $p \geq 1$. With at hand independent copies $\{Z_1, \ldots Z_n\}$ from Z, we aim at estimating a parameter defined through the CMR

$$\mathbb{E}\left[g(Z,\theta_0)|X\right] = 0 \quad \text{a.s.} \tag{2.1}$$

We make the following identifiability assumption of θ_0.

Assumption 1. *(i) The parameter space* Θ *is compact. (ii)* θ_0 *is the unique value in* Θ *satisfying (2.1), that is* $\mathbb{E}\left[g(Z,\theta)|X\right] = 0$ *a.s.* $\Rightarrow \theta = \theta_0$.

We consider a sequence of non-random positive definite (p.d.) weighting matrices $W_n(\cdot)$ and the criterion

$$\begin{aligned} M_{n,h}(\theta) &= \frac{1}{2n(n-1)} \sum_{1 \leq i \neq j \leq n} g'(Z_i,\theta) W_n^{-1/2}(X_i) W_n^{-1/2}(X_j) g(Z_j,\theta) K_{ij}\,, \\ \text{where} \quad K_{ij} &= \frac{1}{h^q} K\left(\frac{X_i - X_j}{h}\right), \quad 1 \leq i \neq j \leq n\,, \end{aligned} \tag{2.2}$$

with a multivariate kernel $K(\cdot)$ and $h = h_n$ a sequence of bandwidth parameters.[1] Discrete covariates U with finite support could be handled by multiplying each term by the indicator function $\mathbb{I}(U_i = U_j)$ and our proofs would easily adapt. For the sake of simplicity, we do not formally consider this possibility in what follows. Our estimator is

$$\tilde{\theta}_{n,h} = \arg\min_{\Theta} M_{n,h}(\theta)\,.$$

[1] Russell Davidson suggested to include equal indexes in the double sum. Our proofs would easily adapt with this modification, but we do not pursue further this suggestion because unreported simulation results do not indicate any general advantage in favor of this modification.

Our estimator cannot be written in the form considered by Carrasco and Florens (2000). When h tends to zero, the SMD estimator belongs to the class of MINPIN estimators studied by Andrews (1994). We cannot however use his general results when considering our estimator as a process indexed by the bandwidth.

When $W_n(X)$ is the identity matrix for any X, our criterion is the statistic studied by Delgado, Dominguez, and Lavergne (2005), a generalization of the one introduced by Zheng (1996) and Li and Wang (1996) for specification testing of regression models. When h tends to zero, the criterion has limit

$$\mathbb{E}\left[g'(Z,\theta)\mathbb{E}\left[g(Z,\theta)|X\right]f(X)\right] = \mathbb{E}\left[\mathbb{E}\left[g'(Z,\theta)|X\right]\mathbb{E}\left[g(Z,\theta)|X\right]f(X)\right]\,,$$

where $f(\cdot)$ is the density of X. Hence, provided a consistent estimator for θ_0, the statistic can be used for testing (2.1). Here we use the statistic for estimation purposes and we thus do not assume the existence of a preliminary consistent estimator. Our criterion estimates a (density-weighted) distance of $\mathbb{E}\left[g(Z,\theta)|X\right]$ to zero when h tends to zero, this provides a first justification for the label *smooth minimum distance*.

For h fixed, say $h = 1$,

$$2\frac{n-1}{n}M_{n,1}(\theta) = \int_{\mathbb{R}^q}\left|n^{-1}\sum_{j=1}^{n} g(Z_j,\theta)\exp(it'X_j)\right|^2 \mathcal{F}\left[K\right](t)\,dt - n^{-2}\sum_{j=1}^{n} g^2(Z_j,\theta)K(0)\,.$$

The first and dominant term is akin to the Integrated Conditional Moment criterion introduced by Bierens (1982) for specification testing in regression models. Our criterion also resembles the one proposed by Dominguez and Lobato (2004), which for a real-valued $g(\cdot,\cdot)$ writes

$$\frac{1}{n^3}\sum_{k=1}^{n}\left[\sum_{i=1}^{n} g(Z_i,\theta)\mathbb{I}(X_i \leq X_k)\right]^2 = \frac{1}{n^2}\sum_{i,j=1}^{n} g(Z_i,\theta)g(Z_j,\theta)\left[\frac{1}{n}\sum_{k=1}^{n}\mathbb{I}(X_i \leq X_k)\mathbb{I}(X_j \leq X_k)\right].$$

By contrast to our criterion, the weight in the above double sum depends on all observations X_i and may vary from 1 to $1/n$. Our criterion has then less variability, and this in turn can reduce variability in parameter estimation, as illustrated by our simulations results.

2.2 Consistency

To understand why our estimator is consistent even when h does not tend to zero, keep $W_n(X)$ equal to the identity matrix for simplicity. Then

$$\begin{aligned}
\mathbb{E}M_{n,h}(\theta) &= \frac{1}{2}\mathbb{E}\left[g'(Z_1,\theta)g(Z_2,\theta)h^{-q}K\left((X_1-X_2)/h\right)\right] \qquad (2.3)\\
&= \frac{1}{2}(2\pi)^{-q/2}\,\mathbb{E}\left[g'(Z_1,\theta)g(Z_2,\theta)\int_{\mathbb{R}^q}\exp\left(it'(X_1-X_2)\right)\mathcal{F}\left[K\right](ht)\,dt\right]\\
&= \frac{1}{2}(2\pi)^{q/2}\sum_{k=1}^{r}\left\{\int_{\mathbb{R}^q}\left|\mathcal{F}\left[\mathbb{E}[g^{(k)}(Z,\theta)|X=\cdot]f(\cdot)\right](t)\right|^2\mathcal{F}\left[K\right](ht)\,dt\right\}\ ,
\end{aligned}$$

This equation shows that the criterion estimates a weighted L^2-distance of the Fourier transform of $\mathbb{E}[g(Z,\theta)|X=\cdot]f(\cdot)$ to zero, thus providing a second justification for its label. Since the expectation of the criterion accounts for the Fourier transform of $\mathbb{E}\left[g(Z,\theta)|X\right]$ at all frequencies, it yields a consistent estimator independently of h. Indeed, if $\mathcal{F}\left[K\right](\cdot)$ is strictly positive on $\mathbb{R}^q$, then using the unicity of the Fourier transform and Assumption 1,

$$\begin{aligned}
\mathbb{E}M_{n,h}(\theta)=0 \quad&\Leftrightarrow\quad \mathcal{F}\left[\mathbb{E}[g^{(k)}(Z,\theta)|X=\cdot]f(\cdot)\right](t)=0 \quad \forall\, t\in\mathbb{R}^q,\ k=1,\ldots r\\
&\Leftrightarrow\quad \mathbb{E}[g(Z,\theta)|X]f(X)=0 \quad \text{a.s.} \Leftrightarrow \theta=\theta_0\ .
\end{aligned}$$

A necessary condition for consistency is then the strict positivity of the Fourier transform of $K(\cdot)$. It is fulfilled for instance by products of the triangular, normal, logistic (see Johnson, Kotz, and Balakrishnan, 1995, Section 23.3), Student (including Cauchy, see Hurst, 1995), or Laplace densities. It is then clear that $\tilde{\theta}_{n,h}$ is consistent for θ_0 provided the convergence $M_{n,h}(\theta)$ of the process to its limit uniformly in θ and h. Let us introduce our basic assumptions.

Assumption 2. *(i) $K(\cdot)$ is a symmetric, bounded function, with integral equal to one, and with strictly positive Fourier transform on $\mathbb{R}^q$. (ii) The class of all functions $(x,\bar{x})\mapsto K((x-\bar{x})/h)$, $x,\bar{x}\in\mathbb{R}^q$, $h>0$, is Euclidean for a constant envelope.*

Symmetry of the kernel is not strictly speaking necessary here, but leads to simpler proofs later on. The Euclidean property is a mild one for parametric families of functions. We refer to Nolan and Pollard (1987), Pakes and Pollard (1989), and Sherman (1994a) for the definition and properties of Euclidean families.[2] Assumption 2-(ii) is also needed when studying the uniform in bandwidth properties of kernel-type estimators, see the definition of "regular"

[2] In recent statistical work, Euclidean families are also called VC classes.

kernels in Einmahl and Mason (2005). Nolan and Pollard (1987), among others, provide some sufficient conditions for it, which are fulfilled by our above examples.

Assumption 3. *For all n, $W_n(\cdot)$ is a $r \times r$ symmetric p.d. non-random matrix function with $0 < \inf_n \inf_u \lambda_{\min}(W_n(u)) \leq \sup_n \sup_u \lambda_{\max}(W_n(u)) < \infty$. There exists a symmetric p.d. matrix function $W(\cdot)$ such that $W_n(u) - W(u) = o(1)$ for all $u \in \mathbb{R}^q$.*

Assumption 4. *(i) The function $\sup_\theta \| \mathbb{E}[g(Z,\theta) \mid X = \cdot] \| f(\cdot)$ is in $L^1 \cap L^2$. For all x, the map $\theta \mapsto \mathbb{E}[g(Z,\theta) \mid X = x]$ is continuous. (ii) The families $\mathcal{G}_k = \{g^{(k)}(\cdot,\theta) : \theta \in \Theta\}$, $1 \leq k \leq r$, are Euclidean for an envelope G with $\mathbb{E}G^2 < \infty$.*

Assumption 3 ensures that $W_n^{-1/2}(\cdot)$ is well-defined and the spectral radius of $W_n^{-1/2}(\cdot)$ is uniformly bounded. It implies that $0 < \inf_u \lambda_{\min}(W(u)) \leq \sup_u \lambda_{\max}(W(u)) < \infty$. Assumption 4 as a whole does not require the continuity of the functions $\theta \mapsto g(z,\theta)$. Assumption 4-(i) ensures that $\mathbb{E}M_{n,h}(\theta)$ is continuous as a function of θ and h. Assumptions 2-(ii), 4-(ii), and the good behavior of the spectral radius of $W_n^{-1/2}(\cdot)$ guarantee that the family of functions

$$\mathcal{G}_n = \{g'(z,\theta)W_n^{-1/2}(x)W_n^{-1/2}(\bar{x})g(\bar{z},\theta)K((x-\bar{x})/h) : \theta \in \Theta, h > 0\}$$

is uniformly Euclidean for a squared integrable envelope, see Lemma 2.14-(ii) of Pakes and Pollard (1989). Here, *uniformly* means that the envelope and the constants in the definition of the Euclidean family are independent of n.

Theorem 2.1. *For an i.i.d. sample and under Assumptions 1–4, $\tilde{\theta}_{n,h} - \theta_0 = o_p(1)$ uniformly over $h \in \{h_0 \geq h > 0 : nh^{2q} \geq \ln(n+1)\}$ for an arbitrary finite $h_0 > 0$, i.e.*[3]

$$\sup_{h_0 \geq h > 0,\ nh^{2q} \geq \ln(n+1)} \|\tilde{\theta}_{n,h} - \theta_0\| = o_p(1)\,.$$

A few remarks are useful. First, the result easily extends to any approximate estimator such that $M_{n,h}(\tilde{\theta}_{n,h}) \leq \min_\Theta M_{n,h}(\theta) + o_p(1)$ uniformly in h. Second, consistency is obtained under more general conditions that the ones imposed for EL-type estimators, see e.g. Kitamura, Tripathi, and Ahn (2004), who impose smoothness of the function $g(\cdot,\cdot)$ and more stringent conditions on the bandwidth. Third, the strict positivity of $\mathcal{F}[K](\cdot)$ can be weakened to positivity if X has a bounded support. In that case, Equation (2.3) yields that $\mathbb{E}M_{n,h}(\theta) = 0$ iff $\mathcal{F}\left[\mathbb{E}[g^{(k)}(Z,\theta)|X = \cdot]f(\cdot)\right](t) = 0$ for all t in a neighborhood of 0, and this yields $\theta =$

[3]Here and in what follows, we abstract from measurability issues of the suprema with respect to h.

θ_0 using Theorem 1 of Bierens (1982). This allows in particular for higher-order kernels taking negative values, as for instance the normalized sinc kernel whose Fourier transform is a uniform density. Fourth, one could allow $W_n(\cdot)$ to depend on θ_0 and another parameter b, as when $W_n(\cdot) = \mathbb{E}\left[\widehat{W}_n(\cdot, \theta_0)\right]$ with $\widehat{W}_n(\cdot, \theta_0)$ a nonparametric estimator of an unknown matrix $W(\cdot, \theta_0)$. We consider this possibility later on, for now we note that our results would carry over assuming that Assumption 3 holds uniformly in b and that the class of matrix-valued functions $W_n(\cdot; b)$ indexed by b is Euclidean entrywise for a constant envelope. Last, allowing $W_n(\cdot)$ to depend on θ to analyze a continuously updated estimator require a more detailed analysis that could be the topic of further work.

2.3 Asymptotic Normality

Let us make the following supplementary assumptions.

Assumption 1. *(iii) θ_0 belongs to the interior of Θ.*

Assumption 4. *(iii) $\mathbb{E}G^4 < \infty$. (iv) There exists a neighborhood of θ_0 and a constant $c > 0$ such that for all θ in that neighborhood, $\mathbb{E}\left\|g(Z, \theta) - g(Z, \theta_0)\right\|^2 \leq c\|\theta - \theta_0\|$. (v) The components of $\nabla_\theta \tau(\cdot, \theta_0) f(\cdot)$ are in $L^1 \cap L^2$. (vi) The components of $\operatorname{Var}\left[g(Z, \theta_0)|X = \cdot\right] f(\cdot)$ are in $L^1 \cap L^2$.*

Assumption 5. *(i) For any x, all second partial derivatives of $\tau(x, \cdot) = \mathbb{E}\left[g(Z, \cdot)|X = x\right]$ exist on a neighborhood $\mathcal{N}$ of θ_0 independent on x. (ii) There exists a real-valued function $H(\cdot)$ with $\mathbb{E}H^4 < \infty$ and some $a \in (0, 1]$ such that*

$$\|\mathrm{H}_{\theta,\theta}\tau^{(k)}(X, \theta) - \mathrm{H}_{\theta,\theta}\tau^{(k)}(X, \theta_0)\| \leq H(X)\|\theta - \theta_0\|^a \quad \forall\, \theta \in \mathcal{N} \qquad k = 1, \ldots r\,.$$

Assumption 5 is implied by the following condition.

Condition 1. *(i) For all z, all second partial derivatives of $g(z, \cdot)$ exist on a neighborhood $\mathcal{N}$ of θ_0 independent on z. (ii) There exists a real-valued function $\tilde{H}(\cdot)$ with $\mathbb{E}\tilde{H}^4 < \infty$ and $a \in (0, 1]$ such that*

$$\|\mathrm{H}_{\theta,\theta} g^{(k)}(Z, \theta) - \mathrm{H}_{\theta,\theta} g^{(k)}(Z, \theta_0)\| \leq \tilde{H}(Z)\|\theta - \theta_0\|^a \quad \forall \theta \in \mathcal{N} \qquad k = 1, \ldots r\,.$$

Under Condition 1, $\mathbb{E}\|g(Z,\theta)-g(Z,\theta_0)\|^2 = O(\|\theta-\theta_0\|^2)$, so Assumption 4-(iv) is not restrictive. For our general results, we do not require differentiability of $g(x,\theta)$ and we impose only 4-(iv), which is precisely what is needed in conditional quantile restriction models where Condition 1 fails, see e.g. Equation (A.11) in Zheng (1998). By Assumption 3, $g_n(Z,\theta) = W_n^{-1/2}(X)g(Z,\theta)$ also satisfies 4-(iv), and $\tau_n(X,\theta) = W_n^{-1/2}(X)\tau(X,\theta)$ inherits the smoothness properties of $\tau(X,\theta)$.

Let $\mathcal{F}_n = \{\phi_{n,h}(\cdot) : h \in [0,h_0]\}$ be the family of functions

$$\phi_{n,h}(z) = \mathbb{E}\left[\nabla_\theta \tau(X,\theta_0) W_n^{-1/2}(X) h^{-q} K\left((x-X)/h\right)\right] W_n^{-1/2}(x) g\left(z,\theta_0\right), \quad \text{for } h \in (0,h_0],$$

and $\phi_{n,0}(z) = \nabla_\theta \tau(x,\theta_0) W_n^{-1}(x) g\left(z,\theta_0\right) f(x)$. Define similarly $\phi_h(\cdot)$ for $h \in [0,h_0]$ with $W(\cdot)$ in place of $W_n(\cdot)$. We denote by $\{\mathbb{G}_n \phi_{n,h} : h \in [0,h_0]\}$ the sequence of centered empirical processes indexed by the families $\mathcal{F}_n$, that is $\mathbb{G}_n \phi_{n,h} = n^{-1/2}\sum_{i=1}^n \phi_{n,h}(Z_i) - \mathbb{E}\phi_{n,h}(Z_i) = n^{-1/2}\sum_{i=1}^n \phi_{n,h}(Z_i)$. Under our following Assumption 6, the process $\{\mathbb{G}_n \phi_{n,h} : h \in [0,h_0]\}$ weakly converges to a tight zero-mean Gaussian process with covariance function $\Delta_{h_1,h_2} = \mathbb{E}\left[\phi_{h_1}(Z)\phi_{h_2}(Z)\right] - \mathbb{E}\phi_{h_1}(Z)\mathbb{E}\phi_{h_2}(Z)$, which is finite by Assumption 3 and 4. We introduce a general condition that allows to analyze the above process. We say that a sequence of real-valued functions ψ_n satisfies Condition (E) with kernel $K(\cdot)$ for an envelope $\Psi(\cdot)$ if the class of functions

$$\{x \mapsto \int \psi_n(x-uh)K(u)du : h \in [0,h_0]\}$$

is uniformly Euclidean for the envelope $\Psi(\cdot)$. Sufficient mild conditions on $\psi_n(\cdot)$ and $K(\cdot)$ that guarantee Condition (E) are provided in Appendix A. In particular, it is sufficient that the $\psi_n(\cdot)$ belong to some Sobolev space of functions, or are Hölder continuous on their support.[4]

Assumption 6. *(i) The components of* $\nabla_\theta \tau_n(\cdot,\theta_0)f(\cdot)$ *satisfy Condition* (E) *with kernel* $K(\cdot)$ *for an envelope* Φ_1 *with* $\mathbb{E}\Phi_1^a < \infty$ *for some* $a \geq 4$. *(ii) The components of* $\mathrm{H}_{\theta,\theta}\tau_n^{(k)}(\cdot,\theta_0)f(\cdot)$, $1 \leq k \leq r$ *and* $H(\cdot)f(\cdot)$ *satisfy Condition* (E) *with kernel* $|K(\cdot)|$ *for an envelope* Φ_2 *with* $\mathbb{E}\Phi_2^a < \infty$ *for some* $a \geq 4/3$.

Let us define the non-random matrices

$$V_{n,h} = \mathrm{H}_{\theta,\theta}\mathbb{E}M_{n,h}(\theta_0) = \mathbb{E}\left[\nabla_\theta \tau_n(X_1,\theta_0)\nabla'_\theta \tau_n(X_2,\theta_0) h^{-q} K\left((X_1-X_2)/h\right)\right] \text{ for } h \in (0,h_0],$$

[4] Condition (E) can be weakened to a uniform entropy condition, as in van der Vaart (1998, Theorem 19.28) or van der Vaart and Wellner (1996, Theorem 2.11.22). As we need to impose Euclidean conditions to investigate the rate of different first and second-order degenerate U-process, we use such conditions throughout.

and $V_{n,0} = \lim_{h \downarrow 0} V_{n,h} = \mathbb{E}\left[\nabla_\theta \tau_n(X, \theta_0) \nabla_\theta \tau_n(X, \theta_0) f(X)\right]$, which follows from Assumption 5-(iii) and arguments similar to those in Equation (2.3). The matrices V_h and V_0 are similarly defined replacing $W_n(\cdot)$ by $W(\cdot)$, see below.

Lemma 2.2. *Under Assumptions 3 and 4(v),* $\sup_{n,h} \lambda_{\max}(V_{n,h}) < \infty$.

Theorem 2.3. *Let* $\mathcal{H}_n = \left\{ h_0 \geq h > 0 : nh^{4q/\alpha} \geq C \right\}$ *for arbitrary constants* h_0, $C > 0$, *and* $\alpha \in (0, 1)$. *For an i.i.d. sample, under Assumptions 1–6 and* $\inf_{n,h} \lambda_{\min}(V_{n,h}) > 0$, $\sqrt{n}\left(\tilde{\theta}_{n,h} - \theta_0\right) + V_{n,h}^{-1} \mathbb{G}_n \phi_{n,h} = o_p(1)$ *uniformly in* $h \in \mathcal{H}_n$, *and* $\{\mathbb{G}_n \phi_{n,h} : h \in [0, h_0]\}$ *weakly converges to a tight zero-mean Gaussian process.*

Our theorem readily yields that $\sqrt{n}\left(\tilde{\theta}_{n,h} - \theta_0\right)$ weakly converges to a tight zero-mean Gaussian process with covariance $V_{h_1}^{-1} \Delta_{h_1,h_2} V_{h_2}^{-1}$, where

$$V_h = \mathbb{E}\left[\nabla_\theta \mathbb{E}\left[g(Z_1, \theta_0) | X_1\right] W^{-1/2}(X_1) W^{-1/2}(X_2) \nabla'_\theta \mathbb{E}\left[g(Z_2, \theta_0) | X_2\right] h^{-q} K\left((X_1 - X_2)/h\right)\right] .$$

For most purposes, our interest lies on its asymptotic variance, that is $V_h^{-1} \Delta_{h,h} V_h^{-1}$, where

$$\begin{aligned} \Delta_{h,h} \;=\; & \mathbb{E}\Big[\nabla_\theta \mathbb{E}\left[g(Z_1, \theta_0) | X_1\right] W^{-1/2}(X_1) W^{-1/2}(X_2) \mathrm{Var}\left[g(Z_2, \theta_0) | X_2\right] W^{-1/2}(X_2) \\ & \qquad W^{-1/2}(X_3) \nabla'_\theta \mathbb{E}\left[g(Z_3, \theta_0) | X_3\right] h^{-2q} K\left((X_1 - X_2)/h\right) K\left((X_2 - X_3)/h\right)\Big] . \end{aligned}$$

A direct consequence of our uniform in bandwidth theory is that one can use a data-dependent sequence of bandwidths that belongs to $\mathcal{H}_n$. As also shown in our proofs section, a similar uniform-in-bandwidth result obtains for $\left\{ h_0 \geq h > 0 : nh^{2q/\alpha} \geq C \right\}$ under Condition 1. This is essentially the same as Andrews' (1994) general condition for MINPIN that the preliminary nonparametric estimator should converge faster than $n^{-1/4}$. Indeed, that $\sqrt{nh^q}$ is strictly larger than $n^{1/4}$ is equivalent to the requirement that nh^{2q} diverges. A similar restriction is imposed by Donald, Imbens and Newey (2003) for GMM with an increasing number of moment conditions, and a stronger one is required for asymptotics of their EL estimator.

We end this section by a comment on one of our assumptions.

Lemma 2.4. *Under Assumptions 3 and 4(v), if* $\mathcal{F}\left[K\right](ht) \geq \mathcal{F}\left[K\right](h_0 t)$ $\forall\ t \in \mathbb{R}^q$, $\forall h \in [0, h_0]$, $\mathrm{H}_{\theta,\theta} \mathbb{E}\left[\tau'(X, \theta_0) \tau(X, \theta_0)\right]$ *positive definite implies* $\liminf_n \inf_h \lambda_{\min}(V_{n,h}) > 0$.

The condition on the kernel is fulfilled by products of normal, logistic, Laplace, and Student densities. About the other condition, note that if we knew $\tau(X, \theta)$, we could minimize $\mathbb{E}\left[\tau'(X, \theta_0) \tau(X, \theta_0)\right]$ to obtain θ_0. The positive definiteness of the Hessian at θ_0 is thus quite natural. Hence the assumption $\inf_{n,h} \lambda_{\min}(V_{n,h}) > 0$ is not unduly restrictive.

2.4 Study Under Misspecification

We now study our estimator under misspecification. As previously argued, this is useful at least as a "robustness" check. As we now show, the behavior of the SMD estimator is very similar whether misspecification exists or not, and specifically is always $\sqrt{n}$-consistent. While no formal result has established the properties under misspecification of alternative estimators methods referred to in the Introduction, Schennach (2007) shows that the excellent properties of EL estimator degrades enormously under the slightest misspecification, causing the loss of $\sqrt{n}$-consistency, and provides an in-depth discussion. In particular, she argues that under misspecification the implied EL probabilities place large weight on a few extreme observations to satisfy the moment restrictions. By contrast, SMD estimation *does not impose* the CMR, but aims at *matching them at best*.

Define the pseudo-true value $\bar{\theta}_{n,h}(W_n) = \bar{\theta}_{n,h} = \arg\min_{\Theta} \mathbb{E}M_{n,h}(\theta)$, which we assume to be unique.[5] Note that for each n the criterion $\mathbb{E}M_{n,h}(\theta)$ is continuous as a function of θ and h so that $\bar{\theta}_{n,h}$ can be extended by continuity to

$$\bar{\theta}_{n,0} = \arg\min_{\Theta} \mathbb{E}\left\{\mathbb{E}\left[g'(Z,\theta)|X\right] W_n^{-1}(X)\mathbb{E}\left[g(Z,\theta)|X\right] f(X)\right\} .$$

Let $\bar{\mathcal{F}}_n = \{\bar{\phi}_{n,h}(\cdot) : h \in [0,h_0]\}$, where

$$\bar{\phi}_{n,h}(z) = \mathbb{E}\left[\nabla_{\theta}\tau(X,\bar{\theta}_{n,h})W_n^{-1/2}(X)h^{-q}K\left((x-X)/h\right)\right] W_n^{-1/2}(x)g(z,\bar{\theta}_{n,h}),$$

and $\bar{\phi}_{n,0}(z) = \nabla_{\theta}\tau(x,\bar{\theta}_{n,0})f(x)W_n^{-1}(x)g\left(z,\bar{\theta}_{n,0}\right)$. Let $\{\mathbb{G}_n\bar{\phi}_{n,h} : h \in [0,h_0]\}$ be the sequence of centered empirical processes indexed by the families $\bar{\mathcal{F}}_n$,

$$\begin{aligned}\bar{V}_{n,h} &= \mathrm{H}_{\theta,\theta}\mathbb{E}M_n(\bar{\theta}_{n,h}) = \mathbb{E}\left[\nabla_{\theta}\tau_n(X_1,\bar{\theta}_{n,h})\nabla'_{\theta}\tau_n(X_2,\bar{\theta}_{n,h})h^{-q}K\left((X_1-X_2)/h\right)\right] \\ &\quad + \sum_{k=1}^{r}\mathbb{E}\left[\mathrm{H}_{\theta,\theta}\tau_n^{(k)}(X_1,\bar{\theta}_{n,h})g_n^{(k)}(X_2,\bar{\theta}_{n,h})h^{-q}K\left((X_1-X_2)/h\right)\right], \qquad (2.4)\end{aligned}$$

and $\bar{V}_{n,0} = \lim_{h\downarrow 0}\bar{V}_{n,h} = \mathrm{H}_{\theta,\theta}\mathbb{E}M_n(\bar{\theta}_{n,0})$. To derive an asymptotic representation, we need to strengthen our assumptions.

Assumption M4. *(i) Each $\bar{\theta}_{n,h}$ is unique and there exists a subset Θ_M of the interior of Θ such that for each n,h there is a ball $B(\bar{\theta}_{n,h},r)$ in Θ_M with r independent of n and h. (ii) There exists a constant $c>0$ such that for all $\theta \in \Theta_M$, $\mathbb{E}\left\|g(Z,\theta_1)-g(Z,\theta_2)\right\|^2 \le c\|\theta_1-\theta_2\|$.*

[5] When W_n does not depend on n, $\bar{\theta}_{n,h}$ depends only on h.

(iii) The components of $\nabla_\theta \tau(\cdot, \theta_1) f(\cdot)$ *and of* $\mathbb{E}\left[g(Z,\theta_1)g'(Z,\theta_2)|X=\cdot\right] f(\cdot)$, $\theta_1, \theta_2 \in \Theta_M$, *are uniformly bounded in* $L^1 \cap L^2$. *(iv) The components of* $\mathbb{E}\left[g(Z,\theta_1)g'(Z,\theta_2)|X=\cdot\right]$ *are continuous in* $\theta_1, \theta_2 \in \Theta_M$.

Assumption M5. *(i) For any* x, *all second partial derivatives of* $\tau(x,\cdot) = \mathbb{E}\left[g(Z,\cdot)|X=x\right]$ *exist on* Θ_M. *(ii) There exists a real-valued function* $H(\cdot)$ *with* $\mathbb{E}H^4 < \infty$ *and some* $a \in (0,1]$ *such that*

$$\|\mathrm{H}_{\theta,\theta}\tau^{(k)}(X,\theta_1) - \mathrm{H}_{\theta,\theta}\tau^{(k)}(X,\theta_2)\| \le H(X)\|\theta_1-\theta_2\|^a \quad \forall\ \theta_1,\theta_2 \in \Theta_M \qquad k=1,\ldots r\,.$$

We say that a sequence of real-valued functions $\psi_n(\cdot,\cdot)$ satisfies Condition (ME) with kernel $K(\cdot)$ for an envelope $\Psi(\cdot)$ if for each $n \ge 1$ the class of functions

$$\{x \mapsto \int \psi_n(x-uh,\theta)K(u)du : h \in [0,h_0], \theta \in \Theta_M\}$$

is uniformly Euclidean for the envelope $\Psi(\cdot)$. Condition (ME) is a mild strengthening of (E) to account for the non-constancy of $\bar{\theta}_{n,h}$ in case of misspecification.

Assumption M6. *(i) The components of* $\nabla_\theta \tau_n(\cdot,\cdot) f(\cdot)$ *satisfy Condition* (ME) *with kernel* $K(\cdot)$ *for an envelope* Φ_1 *with* $\mathbb{E}\Phi_1^a < \infty$ *for some* $a \ge 4$. *(ii) The components of* $\mathrm{H}_{\theta,\theta}\tau_n^{(k)}(\cdot,\cdot)f(\cdot)$, $1 \le k \le r$ *satisfy Condition* (ME) *with kernel* $|K(\cdot)|$ *for an envelope* Φ_2 *with* $\mathbb{E}\Phi_2^a < \infty$ *for some* $a \ge 4/3$. *(iii)* $H(\cdot)f(\cdot)$ *satisfies Condition* (E) *with kernel* $|K(\cdot)|$ *for an envelope* Φ_3 *with* $\mathbb{E}\Phi_3^a(X) < \infty$ *for some* $a \ge 4/3$.

Theorem 2.5. *For an i.i.d. sample, under Assumptions 1-(i), 2, 3, 4-(i) to (iii), M4, M5, and M6, if* $\sup_{n,h}\lambda_{\max}(V_{n,h}) < \infty$ *and* $\inf_{n,h}\lambda_{\min}(V_{n,h}) > 0$, $\sqrt{n}\left(\tilde{\theta}_{n,h} - \bar{\theta}_{n,h}\right) + V_{n,h}^{-1}\mathbb{G}_n\bar{\phi}_{n,h} = o_p(1)$ *uniformly in* $h \in \mathcal{H}_n$, *and* $\left\{\mathbb{G}_n\bar{\phi}_{n,h} : h \in [0,h_0]\right\}$ *weakly converges to a tight zero-mean Gaussian process.*

3 SMD-Based Testing for Parameter Restrictions

3.1 Asymptotics

Suppose we want to test the parametric restriction in explicit form

$$H_0 : \theta_0 = R(\gamma_0)\,, \tag{3.5}$$

where $\gamma_0 \in \mathbb{R}^s$ with $s \leq p$ and $R(\cdot)$ is a function from $\Gamma \subset \mathbb{R}^s$ on Θ. Alternatively, one could look at a null hypothesis in implicit form, but the explicit formulation is as general.

Assumption 8. *(i) $R(\cdot)$ is twice continuously differentiable. (ii) Either $\nabla_\gamma R(\gamma_0)$ has rank $\bar{r} = s \geq 1$ or $\bar{r} = 0$.*

The latter case corresponds to the case where all parameters values are completely determined under H_0. The constrained SMD estimator is $\tilde{\theta}^R_{n,h} = \arg\min_{\theta\in\Theta,\theta=R(\gamma)} M_{n,h}(\theta)$. A distance metric statistic for testing H_0 is

$$DM_{n,h} = 2n \left[M_{n,h}\left(\tilde{\theta}^R_{n,h}\right) - M_{n,h}(\tilde{\theta}_{n,h})\right] .$$

This is analog to the test statistic used in a classical GMM context. For smoothed EL, a similar statistic is studied by Kitamura, Tripathi an Ahn (2004) in the differentiable case, and Otsu (2008) for conditional quantile models. One could alternatively consider tests of the Wald, Score or Lagrange Multiplier type. A theoretical advantage of the distance metric test is that it is automatically invariant to the formulation of the null hypothesis.

For $h \in [0, h_0]$, let

$$\Lambda_{n,h}=\left[I_p - V^{1/2}_{n,h}\nabla'_\gamma R(\gamma_0)\left[\nabla_\gamma R(\gamma_0)V_{n,h}\nabla'_\gamma R(\gamma_0)\right]^{-1}\nabla_\gamma R(\gamma_0)V^{1/2}_{n,h}\right]V^{-1/2}_{n,h}\Delta_{n,h,h}V^{-1/2}_{n,h} ,$$

when $\bar{r} = s$ and $\Lambda_{n,h} = V^{-1/2}_{n,h}\Delta_{n,h}V^{-1/2}_{n,h}$ when $\bar{r} = 0$.

Theorem 3.1. *Under the assumptions of Theorem 2.3 and Assumption 8*

i. under H_0, $DM_{n,h} - (\mathbb{G}_n\phi_{n,h})' \Lambda_{n.h} (\mathbb{G}_n\phi_{n,h}) = o_p(1)$ uniformly in $h \in \mathcal{H}_n$.

ii. if H_0 does not hold $\mathbb{P}\left[n^{-1}DM_{n,h} > c\right] \to 1$ uniformly in $h \in \mathcal{H}_n$ for some $c > 0$.

The process $(\mathbb{G}_n\phi_{n,h})' \Lambda_{n.h} (\mathbb{G}_n\phi_{n,h})$ is asymptotically tight and for each h it has an asymptotic weighted sum of chi-squares distribution $M_{p-s}(\cdot, \lambda_h)$, see e.g. Vuong (1989) for the definition of this distribution, where λ_h is the vector of positive eigenvalues of

$$\Lambda_h=\left[I_p - V^{1/2}_h\nabla'_\gamma R(\gamma_0)\left[\nabla_\gamma R(\gamma_0)V_h\nabla'_\gamma R(\gamma_0)\right]^{-1}\nabla_\gamma R(\gamma_0)V^{1/2}_h\right]V^{-1/2}_h\Delta_{h,h}V^{-1/2}_h ,$$

when $\bar{r} = s$, and $\Lambda_h = V^{-1/2}_h\Delta_{h,h}V^{-1/2}_h$ when $\bar{r} = 0$. Hence we label this process an *asymptotically tight weighted sum of chi-squares* process. The distribution of our distance-metric statistic is thus in general non-pivotal. Our result looks familiar: in a maximum-likelihood context, the likelihood-ratio test is asymptotically a weighted sum of chi-squares, as established by Vuong (1989); a similar result obtains in a GMM context, see Marcellino and Rossi (2008). The classical chi-square distribution reappears when the information matrix equality or its analog holds. As a consequence of our results of Section 4, we recover a χ^2_{p-s} when we use an efficient estimator, that is for the optimal weighting matrix and h tending to zero. However the general distribution obtained without imposing this restriction likely provides a more accurate approximation because it accounts for the influence of the smoothing parameter. We note that the previous theorem extends to misspecified models using our results and conditions in Section 2.2, though we do not formally consider such a generalization.

Determining critical values requires estimation of the eigenvalues λ_h and then of the matrix Λ_h. When Condition 1 holds, one can respectively estimate V_h and $\Delta_{h,h}$ by

$$\frac{1}{n(n-1)} \sum_{1\leq i\neq j\leq n} \nabla_\theta g(Z_i,\tilde{\theta}_{n,h}) W_n^{-1/2}(X_i) W_n^{-1/2}(X_j) \nabla'_\theta g(Z_j,\tilde{\theta}_{n,h}) K_{ij} \,,$$

and

$$\frac{1}{n(n-1)(n-2)} \sum_{1\leq i\neq j\neq k\leq n} \nabla_\theta g(Z_i,\tilde{\theta}_{n,h}) W_n^{-1/2}(X_i) W_n^{-1/2}(X_j) \widehat{\mathrm{Var}}\left[g(Z_k,\tilde{\theta}_{n,h})|X_k\right] \times W_n^{-1/2}(X_j) W_n^{-1/2}(X_k) \nabla'_\theta g(Z_k,\tilde{\theta}_{n,h}) K_{ij} K_{jk} \,,$$

where $\widehat{\mathrm{Var}}\left[g(Z_k,\theta)|X_k\right]$ is a nonparametric consistent estimator of $\mathrm{Var}\left[g(Z_k,\theta)|X_k\right]$, see for instance (4.7) below. If $g(\cdot,\cdot)$ is not differentiable, one can use numerical methods similar to the ones in Pakes and Pollard (1989). In what follows, we shall propose another route.

3.2 Bootstrapping SMD

Bootstrapping is popular to approximate the distribution of statistics when asymptotics may not reflect accurately their behavior in small or moderate samples. In particular, wild bootstrap is widely used for hypothesis testing in regression models, see e.g. Mammen (1992) and the references therein. For testing in CMR models, application of wild bootstrap requires generating resamples with the same values for the exogenous variables, but new observations for the endogenous variables. In addition, the bootstrap samples should mimic the behavior of the data under the null hypothesis. This can be done in simple cases, e.g. in regression models, and has been shown to give reliable approximations. In general however, generating bootstrap samples may be difficult or even infeasible: if the model is nonlinear in the endogenous variables, a reduced form may not be available or unique.

We now propose a simple method that allows to circumvent these difficulties if they appear, that applies generally and is easy to implement. Instead of resampling observations, we perturb the objective function and recompute our test statistic using this perturbed objective function. This method has been proposed by Jin, Ying and Wei (2001) and Bose and Chatterjee (2003), see also Chatterjee and Bose (2005) for a similar method applied to Z-estimators. However, they impose conditions that do not hold in our context. More crucially, they do not investigate the use of this method for testing.

Consider n independent identical copies $\{w_i : i = 1, \dots n\}$ of a known positive random variable w with $\mathbb{E}(w) = \mathrm{Var}(w) = 1$ and $\mathbb{E}w^4 < \infty$. Define the perturbed criterion as

$$M^*_{n,h}(\theta) = \frac{1}{2n(n-1)} \sum_{1 \le i \ne j \le n} w_i w_j g'(Z_i, \theta) W_n^{-1/2}(X_i) W_n^{-1/2}(X_j) g(Z_j, \theta) K_{ij} \,. \tag{3.6}$$

With this new criterion, we repeat the estimation process, that is we compute

$$\tilde{\theta}^*_{n,h} = \arg\min_{\theta} M^*_{n,h}(\theta) \,.$$

The method consists in generating a large number of sample draws from the same distribution w so as to determine precisely enough the distribution of the above statistics. In what follows, we show the uniform in bandwidth validity of this method.

Theorem 3.2. *Under the Assumptions of Theorem 2.3, then conditionally on the sample and uniformly over $h \in \mathcal{H}_n$*

i. $\sqrt{n}\left(\tilde{\theta}^*_{n,h} - \tilde{\theta}_{n,h}\right)$ *has asymptotically the same distribution as* $\sqrt{n}\left(\tilde{\theta}_{n,h} - \theta_0\right)$*, that is* $\sup_{h \in \mathcal{H}_n} \sup_u \left| \mathbb{P}\left[\sqrt{n}\left(\tilde{\theta}^*_{n,h} - \tilde{\theta}_{n,h}\right) \le u | Z_1, \dots Z_n\right] - \mathbb{P}\left[\sqrt{n}\left(\tilde{\theta}_{n,h} - \theta_0\right) \le u\right]\right| = o_p(1)$.

ii. $n\left(M^*_{n,h}(\tilde{\theta}^*_{n,h}) - M^*_{n,h}(\tilde{\theta}_{n,h})\right)$ *has asymptotically the same distribution as* $n\left(M_{n,h}(\tilde{\theta}_{n,h}) - M_{n,h}(\theta_0)\right)$.

An heuristic for this result is as follows. Since $\mathbb{E}\left(M^*_{n,h}(\theta) | Z_1, \dots Z_n\right) = M_{n,h}(\theta)$ is minimized at $\tilde{\theta}_{n,h}$, $\tilde{\theta}^*_{n,h}$ is expected to tend to $\tilde{\theta}_{n,h}$ conditionally on the sample. Now, as shown in the proofs section, the perturbed and the original criterion have a similar quadratic expansion in θ. Therefore, the distribution of $n\left(M^*_{n,h}(\tilde{\theta}^*_n) - M^*_{n,h}(\tilde{\theta}_{n,h})\right)$ is close to the one of $n\left(M_{n,h}(\tilde{\theta}_{n,h}) - M_{n,h}(\theta_0)\right)$, and similarly for $\sqrt{n}\left(\tilde{\theta}^*_{n,h} - \tilde{\theta}_{n,h}\right)$ and $\sqrt{n}\left(\tilde{\theta}_{n,h} - \theta_0\right)$. Our result allows the use of the bootstrap method to approximate the distribution of $\tilde{\theta}_{n,h}$, and in particular can be used to determine confidence intervals for a single parameter. It is more usual to use studentized versions of the estimators, and the asymptotic equivalence of their distribution would easily follow. Whether bootstrapping yields a more accurate approximation in that instance would require further analysis that is beyond the scope of this paper.

Part (ii) of our result is the basis for critical values determination in hypothesis testing. To understand how it can be done, consider the decomposition

$$\begin{aligned} DM_{n,h} &= 2n\left[M_{n,h}\left(\tilde{\theta}^R_{n,h}\right) - M_{n,h}\left(R(\gamma_0)\right) - \left(M_{n,h}(\tilde{\theta}_{n,h}) - M_{n,h}(\theta_0)\right)\right] \\ &\quad + 2n\left[M_{n,h}\left(R(\gamma_0)\right) - M_{n,h}(\theta_0)\right] . \end{aligned}$$

The distribution of $DM_{n,h}$ under H_0 is determined by the first term, while consistency is ensured because the last term diverges under the alternative. Hence to approximate the behavior of the statistic under H_0, we need to approximate the first term only. In that aim, we repeat the estimation process under the constraint (3.5), that is we compute

$$\tilde{\theta}^{R*}_{n,h} = \arg\min_{\theta,\theta=R(\gamma)} M^*_{n,h}(\theta) .$$

The bootstrap distance metric test statistic is then defined as

$$DM^*_{n,h} = 2n\left[M^*_{n,h}(\tilde{\theta}^{R*}_{n,h}) - M^*_{n,h}(\tilde{\theta}^R_{n,h}) - \left(M^*_{n,h}(\tilde{\theta}^*_{n,h}) - M^*_{n,h}(\tilde{\theta}_{n,h})\right)\right] .$$

Theorem 3.3. *Under the Assumptions of Theorem 2.3, then conditionally on the sample and uniformly over $h \in \mathcal{H}_n$*

i. Under H_0, $DM^*_{n,h}$ has asymptotically the same distribution as $DM_{n,h}$,

ii. When H_0 does not hold, $DM^*_{n,h} = o_p(n)$.

The last part suffices to obtain a consistent test, since $DM_{n,h}$ diverges at rate n from Theorem 3.1. However, under suitable assumptions, one could use Theorem 2.5 to show that DM^*_n is bounded in probability whether H_0 holds or not, and thus that the bootstrap test has similar local power than the asymptotic one.

4 Efficient SMD Estimation

We now turn to rendering our estimator efficient: this is desirable from a theoretical viewpoint and suggests that the SMD estimator can compare well to competitors in practice. Our Theorem 2.3 readily gives the optimal weighting matrix $W(\cdot)$ that yields a semiparametric efficient estimator as characterized by Chamberlain (1987).

Corollary 4.1. *Under the Assumptions of Theorem 2.3, $\tilde{\theta}_{n,h}$ is semiparametrically efficient uniformly over $h \in \mathcal{H}_n' = \left\{1/\ln(n+1) \geq h > 0 : nh^{4q/\alpha} \geq C\right\}$ for arbitrary $C > 0$ and $0 < \alpha < 1$ if $W(X) = \operatorname{Var}[g(Z,\theta_0)|X] f(X)$.*

By contrast to GMM, the optimal weighting matrix does not involve $\nabla_\theta \mathbb{E}[g(Z,\theta_0)|X]$, and then makes the efficient SMD we shall propose easy to apply even if $g(\cdot,\cdot)$ is not differentiable. Let $\check{\theta}_n$ be a $\sqrt{n}$-consistent SMD estimate of θ_0, computed for instance by choosing $W_n(\cdot) = I$ and any $h \in \mathcal{H}_n$. Consider the nonparametric estimator of the optimal weight matrix-valued function $\operatorname{Var}[g(Z,\theta_0) \mid X = x] f(x)$ defined as

$$\widehat{W}_n(x,\theta) = \frac{1}{nb^q} \sum_{1 \leq k \leq n} g(Z_k,\theta) g'(Z_k,\theta) L((x - X_k)/b) \tag{4.7}$$

where $L(x)$ is a kernel and b is a vanishing bandwidth. By convention, $\widehat{W}_n(x,\theta) = I$ when the right-hand side of the last display is not positive definite. However, the probability of this event vanishes when n grows under our subsequent assumptions. Our estimator is $\widehat{\theta}_{n,h,b} = \arg\min_\Theta \widehat{M}_{n,h,b}(\theta)$, where

$$\widehat{M}_{n,h,b}(\theta) = \frac{1}{2n(n-1)} \sum_{1 \leq i \neq j \leq n} g'(Z_i,\theta) \widehat{W}_n^{-1/2}(X_i,\check{\theta}_n) \widehat{W}_n^{-1/2}(X_j,\check{\theta}_n) g(Z_j,\theta) K_{ij}\,.$$

It is thus in general a two-step estimator. Note that when Condition 1 holds, a one quasi-Newton step around the preliminary estimator is all what is needed. A preliminary estimator for θ_0 may not even be necessary. Consider for instance the case of nonlinear quantile restrictions where $g(Z,\theta) = \mathbb{I}[Y - \mu(X,\theta) \leq 0] - \rho$ for known ρ, e.g. $\rho = 1/2$ for median restrictions. Then $W(x) = \rho(1-\rho) f(x)$, no preliminary estimator is needed, and a one-step efficient estimator obtains under our following assumptions, as to the ones recently proposed by Otsu (2008) and Komunjer and Vuong (2006).

Assumption E2. *(i) $L(\cdot)$ is a density of bounded variation with bounded support and is strictly positive around the origin. (ii) The class of functions $(x,\bar{x}) \mapsto L((x-\bar{x})/h)$, $x,\bar{x} \in \mathbb{R}^q$, $h > 0$, is Euclidean for a constant envelope.*

Assumption E4. *Assumption 4 holds with $\sup_{x \in \mathbb{R}^q} \mathbb{E}[G^8 \mid X = x] < \infty$.*

Assumption E7. *(i) $f(\cdot)$ is bounded away from zero and infinity with bounded support D that can be written as finite unions and/or intersections of sets $\{x : p(x) \geq 0\}$, where $p(\cdot)$*

is a polynomial function. (ii) $W(\cdot) = \mathbb{E}[g(Z,\theta_0)g'(Z,\theta_0) \mid X = \cdot]f(\cdot)$ *is such that* $0 < \inf_u \lambda_{\min}(W(u)) \leq \sup_u \lambda_{\max}(W(u)) < \infty$*. (iii)* $W(\cdot)$ *is Hölder continuous on* D*. (iv) Let* $\omega^2(\cdot,\theta) = \mathbb{E}[g(Z,\theta)g'(Z,\theta) \mid X = \cdot]$*. For* θ *in a neighborhood of* θ_0*, some* $\nu > 2/3$*, and* $c > 0$*,* $\|\omega^2(x,\theta) - \omega^2(x,\theta_0)\| \leq c\|\theta - \theta_0\|^\nu$ *for all* x*.*

Assumption E4 is needed to apply a result from Einmahl and Mason (2005). Assumption E7 corresponds to supplementary restrictions with respect to the previous sections. Part (i) allows for a flexible form of the support of X. Allowing for a vanishing density would involve introducing some trimming into the objective function, as done by Kitamura, Tripathi and Ahn (2004), but this is outside the scope of this work. They also note that trimming does not affect their estimator in practice and in view of our following simulations results we feel confident that the same applies to efficient SMD. Parts (ii) and (iii) ensure that Assumption 3 holds in probability for $W_n(\cdot) = \mathbb{E}\left[\widehat{W}_n(\cdot,\theta_0)\right]$ and that its entries as indexed by b are Euclidean for a constant envelope. Part (iv) allows to control the bias of $\widehat{W}_n(\cdot,\check{\theta})$. Under our assumptions, it is easy to show that $\widehat{\theta}_{n,h,b}$ is consistent by adapting the proof of Theorem 2.1. Focusing on efficiency matters, we consider that h goes to zero and that the bandwidth b is in the same range than h. No relationship between the two bandwidths is required, though in practice they can be chosen related or even equal.

Theorem 4.2. *For an i.i.d. sample, under Assumptions 1, 2, E2, E4, 5, and E7,*

$$\sup_{h,b\in\mathcal{H}'_n} \left|\widehat{M}_{n,h,b}(\theta) - M_{n,h,b}(\theta)\right| = o_p\left(n^{-1} + \|\theta - \theta_0\|/\sqrt{n} + \|\theta - \theta_0\|^2\right) \tag{4.8}$$

uniformly over θ *in* $o(1)$ *neighborhoods of* θ_0*, where* $M_{n,h,b}(\theta)$ *is defined as in (2.2) with* $W_n(x,\theta_0) = \mathbb{E}\left[\widehat{W}_n(x,\theta_0)\right]$*.*

This result ensures the equivalence of $\widehat{\theta}_{n,h,b}$ and the estimator $\tilde{\theta}_{n,h}$ with weighting matrix $W_n(\cdot) = \mathbb{E}\left[\widehat{W}_n(\cdot,\theta_0)\right]$. Now we can apply Theorem 2.3 provided an equivalent of Assumption 6 holds that accounts for the dependence of the weighting matrix on b. We here provide some primitive conditions that together with Assumption E7 ensure such an assumption, though they are likely not the only or weakest possible.

Assumption E6. *Each of the entries of* $\nabla_\theta \tau(\cdot,\theta_0)f(\cdot)$*,* $\mathrm{H}_{\theta,\theta}\tau_n^{(k)}(\cdot,\theta_0)f(\cdot)$*,* $1 \leq k \leq r$ *and* $H(\cdot)f(\cdot)$ *is Hölder continuous on* D*, with possibly different exponents.*

Corollary 4.3. *Under the assumptions of Theorem 4.2 and E6,* $\sqrt{n}\left(\widehat{\theta}_{n,h,b}-\theta_0\right)$ *is asymptotically* $N(0,\Sigma^{-1})$ *with* $\Sigma=\mathbb{E}\left[\nabla_\theta \mathbb{E}\left[g(Z,\theta_0)|X\right]\mathrm{Var}^{-1}\left[g(Z,\theta_0)|X\right]\nabla_\theta' \mathbb{E}\left[g(Z,\theta_0)|X\right]\right]$ *uniformly in* $h,b\in\mathcal{H}_n'$*. Moreover, the results of Section 3 holds for* $\widehat{\theta}_{n,h,b}$ *uniformly in* $h,b\in\mathcal{H}_n'$*.*

5 Small sample study

The first setup is the one considered by Dominguez and Lobato (2004), where

$$Y=\theta_0^2 X+\theta_0 X^2+\varepsilon, \tag{5.9}$$

with $\theta_0=5/4$, $X\sim N(\mu,1)$, and $\varepsilon\sim N(0,1)$ independently of X. The unknown parameter is not globally identified whenever $\mu\neq 0$. Dominguez and Lobato (2004, hereafter DL) illustrate theoretically and through simulations the consequences of lack of global identification on nonlinear least-squares (NLS). Abstracting from this issue, we considered as our benchmark the infeasible efficient NLS estimator based on the knowledge that the model is homoscedastic and optimized locally around the true value of the parameter. We considered three versions of SMD (i) $W=I$ and $h=1$, (ii) $W=I$ and $h=0.3$, (iii) the efficient version with $h=b=0.3$, the two cases $\mu=0$ and $\mu=1$, and two sample sizes, $n=50$ and $n=200$. For implementation, we used a Gaussian kernel. All results are based on 5000 replications.

Figures 1 to 4 compare the densities of the different estimators centered and scaled by $\sqrt{n}$. Table 1 reports the ratios of root mean squared error (RMSE) and mean absolute deviation (MAE) of each estimator with respect to the one of the locally optimized NLS. DL's estimator is more variable than versions (i) and (ii) of SMD. Increasing the sample size does not significantly affect the performances of the latters with respect to NLS, and changing the bandwidth has little effect. The efficient version performs very well compared to NLS, and its accuracy improves when the sample size increases, even though the bandwidths do not adapt to the sample size.

The second setup is the one of Cragg (1983), Newey (1993), and Kitamura, Tripathi and Ahn (2004, herefater KTA), where

$$Y=\beta_1+\beta_2 X+\varepsilon,\quad \mathbb{E}(\varepsilon|X)=0,\quad \mathrm{Var}(\varepsilon|X)=.1+.2X+.3X^2\,, \tag{5.10}$$

with $\beta_1=\beta_2=1$, $\ln X\sim N(0,1)$, and ε is normally distributed. KTA (2004) concluded that in this setup the Smoothed Empirical Likelihood (SEL) works best among various estimators.

As a benchmark, we considered the generalized least squares estimator based on the true variance function, and we computed the feasible version based on the knowledge of the variance functional form. We considered efficient SMD with a Gaussian kernel and $h = b$. Results for SMD are based on 5000 replications, while results for SEL are based on 500 replications as reported by KTA.

Table 2 reports the ratios of root mean squared error (RMSE) and mean absolute deviation (MAE) of each estimator with respect to the infeasible GLS. The considered bandwidths were chosen in the grid $n^{-1/5} \times (2/3, 5/3, 8/3)$ to allow a straightforward comparison with KTA's results. This should not be taken as a recommendation: a bandwidth constant of $8/3$ is pretty large as compared for instance with the simple rule of thumb based on 0.8 times the interquartile range of X, which is 1.45. The efficient SMD performs well compared to the feasible GLS, though the latter relies on the parametric form of the variance. The relative performances of SEL and SMD vary depending on the bandwidth choice. To gain further insight, Figure 5 reports the ratio of RMSE as a function of the bandwidth on a finer grid.[6] The shape of RMSE with respect to the bandwidth is strikingly different for the two estimators. For SEL, RMSE is minimized at a quite large value of the bandwidth for both parameters, and the "optimal" bandwidth does not decrease with the sample size. For SMD, RMSE of the intercept is always minimum at the smallest considered bandwidth, while for the slope the "optimal" bandwidth decreases with the sample size.

We then investigated the behavior of our bootstrap distance-metric statistic under the null hypothesis. We did not explore the power properties of our test, such a study is left for future research. We ran 500 replications for sample sizes $n = 50$ and 100, and for each replication 99 bootstrapped statistics were computed to determine the critical value. For bootstrapping, we used the two-point distribution defined through

$$\mathbb{P}\left[w = \frac{3-\sqrt{5}}{2}\right] = \frac{5+\sqrt{5}}{10} \qquad \text{and } \mathbb{P}\left[w = \frac{3+\sqrt{5}}{2}\right] = \frac{5-\sqrt{5}}{10}\,.$$

We chose this simple distribution with third central moment equal to one in the hope to better approximate the distribution of the statistic, as is the case in simpler setups, see e.g. Mammen (1992). Table 3 reports empirical levels of the test. In all cases, the level accuracy increases when the sample size increases. For Model (5.9), the empirical level accuracy is reasonable for $n = 50$, while somewhat away for $X \sim N(1, 1)$, and very close to the nominal one for

[6]Figures corresponding to SEL were kindly provided by Yuichi Kitamura.

$n = 100$, while the Wald test based on the locally optimized NLS estimator over rejects. For Model (5.10), our results follow a similar general pattern: for relatively large bandwidths, the test over rejects, but this phenomenon fades out with increasing sample size. We also checked that using asymptotic 5% critical values from the chi-square distribution with one degree of freedom for our test yields rejection percentages between 0.2 and 1.3% depending on the bandwidth and sample size, and thus does not constitute a credible alternative in small samples. Tests based on FGLS (Wald and LR tests yield identical results) are severely oversized and are then not reliable either.

To sum up, our SMD estimator performs well in our simulation experiments, is competitive with SEL while it exhibits a different behavior with respect to the bandwidth. Our bootstrap technique yields reliable test levels for moderate sample sizes.

6 Conclusion

We have proposed a smooth minimum distance estimation method for finite-dimensional parameters in models defined by conditional moment restrictions. Our SMD estimator depends on a smoothing parameter but is $\sqrt{n}$-consistent independently of this parameter within a wide range allowing for a fixed one. In our theory, we consider this estimator as a process indexed by the bandwidth and we establish a uniform in bandwidth asymptotic representation. Our results are derived under weaker smoothness conditions than the ones available for competing estimators, so that they readily apply to many models, as conditional quantile restrictions models. We have developed a testing procedure based on a distance-metric statistic. Since the smoothing parameter cannot in practice be chosen arbitrarily close to zero, and thus the behavior of our estimator and test can be badly approximated by asymptotics, we have proposed a new bootstrap method. We have also shown how to obtain an efficient version of the SMD estimator when the bandwidth converges to zero. In practice, both the estimator and the bootstrap method are simple to implement and are found to perform reasonably well in our simulations. The higher-order properties of the estimator, the influence of the bandwidth and the optimal bandwidth choice should be investigated. An overidentification testing procedure based on our optimized criterion needs to be developed. Generalizations to situations where a functional nuisance parameter is present and to time-series contexts also require further study.

7 Proofs

7.1 Preliminary lemmas

In what follows we adopt the notations of Sherman (1993, 1994a) concerning U-statistics. Following his use, we say that for a sequence $\theta_{n,h}$, $H_n(\theta) = o_p(1)$, respectively $O_p(1)$, uniformly over $o_p(1)$ neighborhoods of $\theta_{n,h}$ and uniformly in $h \in \mathcal{H}_n$ if for any sequence of random variables $r_n = o_p(1)$, there exist a sequence $b_n = o_p(1)$, respectively $O_p(1)$, such that $\sup_{n,h\in\mathcal{H}_n} \sup_{\|\theta-\theta_{n,h}\|\leq r_n} |H_n(\theta)| \leq b_n$. The following is an extension of Corollary 8 of Sherman (1994a).

Lemma 7.1. *Let $\mathcal{F}_n = \{f_n(\cdot, \theta, h) : \theta \in \Theta, h > 0\}$ be a class of degenerate functions on $\mathbb{R}^k$, $k \geq 1$, where $f_n(\cdot, \theta_{n,h}, \cdot) \equiv 0$. If*

i. $\mathcal{F}_n$ is Euclidean for an envelope F satisfying $\mathbb{E}F^4 < \infty$ uniformly in n,

ii. There is a ball $B(\theta_{n,h}, r)$ and positive constants a and c, with r, a, and c independent on n and h, such that $\mathbb{E}f_n^2(\cdot, \theta, h) \leq c\|\theta - \theta_{n,h}\|^a$ for all $\theta \in B(\theta_{n,h}, r)$, all $h > 0$, and all n,

then uniformly over $B(\bar{\theta}_{n,h}, r)$ and $h > 0$, and for any $0 < \alpha < 1$

$$n^{k/2}U_n^k f_n(\cdot, \theta, h) = \|\theta - \theta_{n,h}\|^{a\alpha/2} O_p(1) + O_p\left(n^{-\alpha/4}\right).$$

If we assume further that $f_n^2(\cdot, \theta_{n,h}, h) \leq \Phi(\cdot)\|\theta - \theta_{n,h}\|^a$ with $\mathbb{E}\Phi < \infty$, then then uniformly over $B(\bar{\theta}_{n,h}, r)$ and $h > 0$, $n^{k/2}U_n^k f(\cdot, \theta, h) = \|\theta - \theta_{n,h}\|^{a\alpha/2} O_p(1)$ for any $0 < \alpha < 1$.

Proof. For simplicity, write $\mathcal{N}$ for $B(\theta_{n,h}, r_n)$. Following the proof of Sherman (1994a, Corollary 8),

$$\mathbb{E} \sup_{\theta\in\mathcal{N},h>0} \left| n^{k/2}U_n^k f_n(\cdot, \theta, h)\right| \leq \left[\mathbb{E} \sup_{\theta\in\mathcal{N},h>0} U_{2n}^k f_n^2(\cdot, \theta, h)\right]^{\alpha/2}$$

for any $0 < \alpha < 1$. Under the last condition, one readily obtains the desired result. Under Conditions i and ii only,

$$\mathbb{E} \sup_{\theta\in\mathcal{N},h>0} U_{2n}^k f_n^2(\cdot, \theta, h) \leq \sup_{\theta\in\mathcal{N},h>0} \mathbb{E}f_n^2(\cdot, \theta, h) + \sum_{i=1}^{k} \mathbb{E} \sup_{\theta\in\mathcal{N},h>0} U_{2n}^i f_{n,i}(\cdot, \theta, h)$$

where the class of functions $\{f_{n,i} : \theta \in \mathcal{N}, h > 0\}$ is degenerate on $\mathbb{R}^i$. Deduce from Lemma 2.14 of Pakes and Pollard (1989) that these classes are uniformly Euclidean for squared-integrable envelopes F_i, and from Corollary 4 of Sherman (1994a) that $\mathbb{E}\sup_{\theta\in\mathcal{N},h>0} U_{2n}^i f_{n,i}(\cdot, \theta, h) = O(n^{-i/2})$. □

The following lemmas are extensions of Theorems 1 and 2 of Sherman (1993) and Theorems 1 and 2 of Sherman (1994b). The proofs proceed by straightforward modifications of his.

Lemma 7.2. *Let $\theta_{n,h}$ be the minimizer of $M_{n,h}(\theta)$ depending on a bandwidth h, $\mathcal{H}_n$ a set of bandwidths, and let $\bar\theta_{n,h}$ be a minimizer of a function $\bar M_{n,h}(\theta)$ that may also depend on h. If*

i. $\theta_{n,h} - \bar\theta_{n,h} = o_p(1)$ *uniformly in* $h \in \mathcal{H}_n$,

ii. there is a ball $B(\bar\theta_{n,h}, r)$ *and a constant* $\kappa > 0$, *with* r *and* κ *independent on* n *and* h, *such that uniformly in* $h \in \mathcal{H}_n$

$$\bar M_{n,h}(\theta) - \bar M_{n,h}(\bar\theta_{n,h}) \geq (\kappa + o(1)) \|\theta - \bar\theta_{n,h}\|^2 \qquad \forall \theta \in B(\bar\theta_{n,h}, r)\,,$$

iii. for some $\varepsilon_n = o(1)$ *and uniformly over* $o_p(1)$ *neighborhood of* $\bar\theta_{n,h}$ *and* $h \in \mathcal{H}_n$,

$$M_{n,h}(\theta) = \bar M_{n,h}(\theta) + \|\theta - \bar\theta_{n,h}\| O_p(1/\sqrt{n}) + \|\theta - \bar\theta_{n,h}\|^2 o_p(1) + O_p(\varepsilon_n)\,,$$

then $\|\theta_{n,h} - \bar\theta_{n,h}\| = O_p\left[\max\left(\varepsilon_n^{1/2}, n^{-1/2}\right)\right]$ *uniformly in* $h \in \mathcal{H}_n$.

Lemma 7.3. *Let* $\theta_{n,h}$ *be as in Lemma 7.2. Suppose* $\theta_{n,h} - \bar\theta_{n,h} = O_p(1/\sqrt{n})$ *uniformly in* $h \in \mathcal{H}_n$, *that the limit points of the sequence* $\bar\theta_{n,h}$ *are in the interior of* Θ, *and that uniformly over* $O_p(1/\sqrt{n})$ *neighborhoods of* $\bar\theta_{n,h}$,

$$M_{n,h}(\theta) = M_{n,h}(\bar\theta_{n,h}) + \frac{1}{2}\left(\theta - \bar\theta_{n,h}\right)' V_{n,h}\left(\theta - \bar\theta_{n,h}\right) + \frac{1}{\sqrt{n}} A'_{n,h}\left(\theta - \bar\theta_{n,h}\right) + o_p(1/n) \tag{7.11}$$

where $V_{n,h}$ *is a sequence of positive definite matrices such that* $0 < c_{\min} \leq \lambda_{\min}(V_{n,h}) \leq \lambda_{\max}(V_{n,h}) \leq c_{\max} < \infty$ *for some* $c_{\min}$ *and* $c_{\max}$ *independent on* n *and* h, *and* $A_{n,h} = O_p(1)$ *uniformly in* $h \in \mathcal{H}_n$. *Then* $\sqrt{n}\left(\theta_{n,h} - \bar\theta_{n,h}\right) + V_{n,h}^{-1} A_{n,h} = o_p(1)$ *uniformly in* $h \in \mathcal{H}_n$.

7.2 Main proofs

In the main proofs, we use a single index n in place of the double indices n and h, e.g. we write M_n instead of $M_{n,h}$.

Proof of Theorem 2.1. Replacing $g(Z,\theta)$ by $g_n(Z,\theta) = W_n^{-1/2}(X) g(Z,\theta)$ in (2.3) yields

$$\begin{aligned}
\mathbb{E} M_n(\theta) = 0 \quad &\Leftrightarrow \quad \mathcal{F}\left[\mathbb{E}\left[g_n^{(k)}(Z,\theta) | X = \cdot\right] f(\cdot)\right](t) = 0 \quad \forall\, t \in \mathbb{R}^q,\ k = 1, \ldots r \\
&\Leftrightarrow \quad W_n^{-1/2}(X) \mathbb{E}\left[g(Z,\theta)|X\right] = 0 \quad \text{a.s.} \Leftrightarrow \theta = \theta_0\,,
\end{aligned}$$

as $W_n(X)$ is positive definite. Since $\mathbb{E} M_n(\theta)$ is continuous in θ from Assumption 4-(ii) as well as in h, see (2.3), we have that $\forall \varepsilon > 0$, $\exists \mu > 0$ such that $\inf_{\|\theta - \theta_0\| \geq \varepsilon, 0 \leq h \leq h_0} \mathbb{E} M_n(\theta) \geq \mu$. The family of functions $\{g'(Z_1,\theta) W_n^{-1/2}(X_1) W_n^{-1/2}(X_2) g(Z_2,\theta) K\left((X_1 - X_2)/h\right) : \theta \in \Theta, h > 0\}$ is Euclidean for a square-integrable envelope by Assumptions 2 and 4, Lemma 22(ii) of Nolan and Pollard

(1987) and Lemma 2.14(ii) of Pakes and Pollard (1989). Thus by Corollary 7 of Sherman (1994a), $\sup_{\theta\in\Theta,h>0}|h^qM_n(\theta)-\mathbb{E}h^qM_n(\theta)| = O_{\mathbb{P}}(n^{-1/2})$. Let $\bar{\mathcal{H}}_n$ the set of bandwidths from the theorem and consider a set on which $\sup_{\theta\in\Theta,h\in\bar{\mathcal{H}}_n}|h^qM_n(\theta)-\mathbb{E}h^qM_n(\theta)| \leq Cn^{-1/2}\ln\ln(n+2)$, whose probability tends to one for any constant $C>0$. On this set,

$$\inf_{\|\theta-\theta_0\|\geq\varepsilon}\inf_{h\in\bar{\mathcal{H}}_n}[M_n(\theta)-M_n(\theta_0)] \geq \inf_{\|\theta-\theta_0\|\geq\varepsilon}\inf_{h\in\bar{\mathcal{H}}_n}\mathbb{E}M_n(\theta) - \left[2C\ln\ln(n+2)/\left(\ln(n+1)\right)^{-1/2}\right]$$

so that $\inf_{\|\theta-\theta_0\|\geq\varepsilon}\sup_{h\in\bar{\mathcal{H}}_n}[M_n(\theta)-M_n(\theta_0)] \geq \mu/2$ for n large enough. Since $M_n(\tilde{\theta}_n)\leq M_n(\theta_0)$, it follows that $\sup_{h\in\bar{\mathcal{H}}_n}\|\tilde{\theta}_n-\theta_0\| < \varepsilon$ with probability tending to one. □

Proof of Lemmas 2.2 and 2.4. For any n, h, and $a\in\mathbb{R}^p$,

$$\begin{aligned} a'V_{n,h}a &= \mathbb{E}\left[a'\nabla_\theta\tau_n(X_1,\theta_0)\nabla'_\theta\tau_n(X_2,\theta_0)a\ h^{-q}K\left(\frac{X_1-X_2}{h}\right)\right] \\ &= (2\pi)^{q/2}\left\{\int_{\mathbb{R}^q}\sum_{k=1}^{r}\left|\mathcal{F}\left[a'\nabla_\theta\tau_n^{(k)}(\cdot,\theta_0)f(\cdot)\right](t)\right|^2\mathcal{F}[K](ht)\,dt\right\}\ , \end{aligned} \tag{7.12}$$

Since $\mathcal{F}[K](ht)\leq(2\pi)^{-q/2}$ for all h, t, and by Assumptions 3 and 4-(v),

$$\sup_{n,h}\lambda_{\max}(V_{n,h}) = \sup_n\lambda_{\max}(V_{n,0}) \leq \lambda_{\max}\left(\mathbb{E}\left[\nabla_\theta\tau(X,\theta_0)\nabla'_\theta\tau(X,\theta_0)f(X)\right]\right)\sup_{n,u}\lambda_{\min}^{-1}(W_n(u)) < \infty\,.$$

If $\mathcal{F}[K](ht)\geq\mathcal{F}[K](h_0t)$ for all t, $h\in[0,h_0]$, $\liminf_n\inf_h\lambda_{\min}(V_{n,h}) = \liminf_n\lambda_{\min}(V_{n,h_0})$ from (7.12). Moreover, $\liminf_n\lambda_{\min}(V_{n,h_0})\geq\lambda_{\min}(V_{h_0})-\limsup_n\|\tilde{V}_{n,h_0}\|_2$, where $\tilde{V}_{n,h_0}=V_{n,h_0}-V_{h_0}$ and $\|\cdot\|_2$ denotes the spectral norm. From Assumption 3 and since the map $W\mapsto W^{-1/2}$ is continuous, see Equation (7.23) below, $\sup_u\lambda_{\max}(W^{-1/2}(u))$ and $\sup_{n,u}\lambda_{\max}(W_n^{-1/2}(u))$ are bounded, and $W_n^{-1/2}(u)-W^{-1/2}(u)=o(1)$ for any u. It follows from the Lebesgue dominated convergence theorem and Assumption 4(v) that $\limsup_n\|\tilde{V}_{n,h_0}\|_2=o(1)$. Therefore $\liminf_n\lambda_{\min}(V_{n,h_0})\geq(1/2)\lambda_{\min}(V_{h_0})$. Using (7.12) and the unicity of the Fourier transform,

$$\lambda_{\min}(V_{h_0})=0 \Leftrightarrow \exists\, a\neq 0:\ a'\nabla_\theta\tau(X,\theta_0)W^{-1/2}(X)f(X)=0 \text{ a.s.} \Leftrightarrow \exists\, a\neq 0:\ a'\nabla_\theta\tau(X,\theta_0)=0 \text{ a.s.}$$

But $a'\mathrm{H}_{\theta,\theta}\mathbb{E}\left[\tau'(X,\theta_0)\tau(X,\theta_0)\right]a = 2\mathbb{E}\left[a'\nabla_\theta\tau(X,\theta_0)\nabla'_\theta\tau(X,\theta_0)a\right]=0$ iff $a=0$. Thus $\lambda_{\min}(V_{h_0})>0$. □

Proof of Theorem 2.3. The proof follows from Parts (ii) to (iv) of Theorem 2.5's proof, setting $\bar{\theta}_n=\theta_0$ and accounting for (2.1). □

Proof of Theorem 2.5. (i) Consistency: Since $\bar{\theta}_n$ is the unique minimizer of $\mathbb{E}M_n(\theta)$, reason as in Theorem 2.1's proof to show that $\sup_{h\in\bar{\mathcal{H}}_n}\|\tilde{\theta}_n-\bar{\theta}_n\|=o_p(1)$.

(ii) $\sqrt{n}$-consistency: Since $\nabla_\theta \mathbb{E} M_n(\bar{\theta}_n) = 0$ and $\inf_{n,h} \lambda_{\min}(V_{n,h}) > 0$, we have uniformly in $h \in \mathcal{H}_n$

$$
\begin{aligned}
&\mathbb{E}M_n(\theta) - \mathbb{E}M_n(\bar{\theta}_n) \\
&= (\theta - \bar{\theta}_n)' \nabla_\theta \mathbb{E}M_n(\bar{\theta}_n) + \frac{1}{2}(\theta - \bar{\theta}_n)' \mathrm{H}_{\theta,\theta}\mathbb{E}M_n(\bar{\theta}_n)(\theta - \bar{\theta}_n) + o(\|\theta - \bar{\theta}_n\|^2) \\
&= \frac{1}{2}(\theta - \bar{\theta}_n)' \bar{V}_{n,h}(\theta - \bar{\theta}_n) + o(\|\theta - \bar{\theta}_n\|^2) \geq \frac{1}{2}\left(\inf_{n,h} \lambda_{\min}(\bar{V}_{n,h}) + o(1)\right)\|\theta - \bar{\theta}_n\|^2 .
\end{aligned}
$$

Now apply Hoeffding's decomposition to $M_n(\theta) - M_n(\bar{\theta}_n)$ and consider the first-order empirical process $\mathbb{P}_n \tilde{l}_\theta$, where $\tilde{l}_\theta(Z_i) = \mathbb{E}[l_\theta(Z_i, Z_j) \mid Z_i] + \mathbb{E}[l_\theta(Z_i, Z_j) \mid Z_j] - 2\mathbb{E}[l_\theta(Z_i, Z_j)]$,

$$
\begin{aligned}
l_\theta(Z_i, Z_j) &= (1/2)\left(g_n'(Z_i, \theta) g_n(Z_j, \theta) - g_n'(Z_i, \bar{\theta}_n) g_n(Z_j, \bar{\theta}_n)\right) h^{-q} K\left((X_i - X_j)/h\right) \\
&= (1/2) g_n'(Z_i, \bar{\theta}_n)\left(g_n(Z_j, \theta) - g_n(Z_j, \bar{\theta}_n)\right) h^{-q} K\left((X_i - X_j)/h\right) \\
&\quad + (1/2)\left(g_n(Z_i, \theta) - g_n(Z_i, \bar{\theta}_n)\right)' g_n(Z_j, \bar{\theta}_n) h^{-q} K\left((X_i - X_j)/h\right) \\
&\quad + (1/2)\left(g_n(Z_i, \theta) - g_n(Z_i, \bar{\theta}_n)\right)'\left(g_n(Z_j, \theta) - g_n(Z_j, \bar{\theta}_n)\right) h^{-q} K\left((X_i - X_j)/h\right) \\
&= l_{1\theta}(Z_i, Z_j) + l_{2\theta}(Z_i, Z_j) + l_{3\theta}(Z_i, Z_j),
\end{aligned}
$$

and $l_{1\theta}(Z_i, Z_j) = l_{2\theta}(Z_j, Z_i)$ by the symmetry of $K(\cdot)$. From Assumption M5,

$$
\begin{aligned}
2\mathbb{E}[l_{1\theta}(Z_i, Z_j) \mid Z_i] &= g_n'(Z_i, \bar{\theta}_n)\mathbb{E}\left[\left(g_n(Z, \theta) - g_n(Z, \bar{\theta}_n)\right) h^{-q} K\left((X_i - X)/h\right) | Z_i\right] \\
&= g_n'(Z_i, \bar{\theta}_n)\left[\int_{\mathbb{R}^q} \nabla_\theta' \tau_n(x, \bar{\theta}_n) f(x) h^{-q} K\left((X_i - x)/h\right) dx\right](\theta - \bar{\theta}_n) \quad (7.13) \\
&\quad + \frac{1}{2} g_n'(Z_i, \bar{\theta}_n) \sum_{k,l=1}^{p}\left(\theta^{(k)} - \bar{\theta}_n^{(k)}\right)\left(\theta^{(l)} - \bar{\theta}_n^{(l)}\right) \\
&\quad \left[\int_{\mathbb{R}^q} \mathrm{H}_{\theta^{(k)}\theta^{(l)}} \tau_n(x, \bar{\theta}_n) f(x) h^{-q} K\left((X_i - x)/h\right) dx\right] + R_{1n}(Z_i, \theta) \quad (7.14)
\end{aligned}
$$

$$
\text{where } \|R_n(Z_i, \theta)\| \leq G(Z_i)\|\theta - \bar{\theta}_n\|^{2+a}\left[\sum_{k=1}^{r}\left(\int_{\mathbb{R}^q} H_n^{(k)}(X_i - hu) f(X_i - hu)|K(u)|\, du\right)^2\right]^{1/2}
$$

and $H_n(\cdot) = W_n^{-1/2}(\cdot) H(\cdot)$. By Assumption M6-(i), the functions $\nabla_\theta \tau_n^{(k)}(\cdot, \bar{\theta}_n) f(\cdot)$, $n \geq 1$ satisfy Condition (ME) for an envelope Φ with $\mathbb{E}\Phi^a(X) < \infty$ for some $a \geq 4$. Use Assumption M4 and Lemma 2.14-(ii) in Pakes and Pollard (1989) to conclude that the family of functions $\widetilde{\phi}_{n,h}'(z)$ indexed by h in (7.13) is uniformly Euclidean for a squared-integrable envelope. Hence $A_n' = \bar{\mathbb{G}}_n \widetilde{\phi}_{n,h}' = O_p(1)$ uniformly in θ and $h \in [0, h_0]$ by Corollary 4 of Sherman (1994a). Similarly, the family of functions in (7.14) is uniformly Euclidean for an integrable envelope. By a version of the Glivenko-Cantelli for families changing with n, see e.g. van de Geer (2000, p.44), the centered empirical sum based on this family of functions is then an $o_p(1)$ uniformly in $h \in [0, h_0]$. Finally, $\left\{G(z)\int_{\mathbb{R}^q} H_n^{(k)}(x - hu) f(x - hu)|K(u)|\, du : h \in [0, h_0]\right\}$ are also uniformly Euclidean for an integrable envelope, so that the (uncentered) empirical sum based on this family of functions is a $O_p(1)$ uniformly in $h \in [0, h_0]$. A similar expansion for $l_{3\theta}$ yields

$$
\begin{aligned}
2\mathbb{E}[l_{3\theta}(Z_i, Z_j) \mid Z_i] &= \left(g_n(Z_i, \theta) - g_n(Z_i, \bar{\theta}_n)\right)' \mathbb{E}\left[\left(g_n(Z, \theta) - g_n(Z, \bar{\theta}_n)\right) h^{-q} K\left(\left(X_i - X\right)/h\right) | Z_i\right] \\
&= \left(g_n(Z_i, \theta) - g_n(Z_i, \bar{\theta}_n)\right)' \\
&\quad \left[\int_{\mathbb{R}^q} \nabla'_\theta \tau_n(x, \bar{\theta}_n) f(x) h^{-q} K\left(\left(X_i - x\right)/h\right) \, dx\right] (\theta - \bar{\theta}_n) \qquad (7.15) \\
&\quad + \frac{1}{2}\left(g_n(Z_i, \theta) - g_n(Z_i, \bar{\theta}_n)\right)' \sum_{k,l=1}^{p} \left(\theta^{(k)} - \bar{\theta}_n^{(k)}\right)\left(\theta^{(l)} - \bar{\theta}_n^{(l)}\right) \\
&\quad \left[\int_{\mathbb{R}^q} \mathrm{H}_{\theta^{(k)}\theta^{(l)}} \tau_n(x, \bar{\theta}_n) f(x) h^{-q} K\left(\left(X_i - x\right)/h\right) \, dx\right] + R_{3n}(Z_i, \theta) \, .
\end{aligned}
$$

Since the function in (7.15) is such that

$$
\mathbb{E}\left|\left(g_n(Z_i, \theta) - g_n(Z_i, \bar{\theta}_n)\right)' \left[\int_{\mathbb{R}^q} \nabla'_\theta \tau_n(x, \bar{\theta}_n) f(x) h^{-q} K\left(\left(X_i - x\right)/h\right) \, dx\right]\right| \to 0
$$

as $\theta - \bar{\theta}_n \to 0$, the centered process based on these functions is an $o_p(1/\sqrt{n})$ uniformly in θ and h by Corollary 8 of Sherman (1994a). The remaining terms can be dealt with similarly. Hence

$$
\mathbb{P}_n \tilde{l}_\theta = \frac{1}{\sqrt{n}} A'_n \left(\theta - \bar{\theta}_n\right) + \|\theta - \bar{\theta}_n\|^2 o_p(1) \, , \qquad (7.16)
$$

uniformly over $o_p(1)$ neighborhoods of $\bar{\theta}_n$ and $h \in [0, h_0]$.

Consider the second order centered degenerate U-process $U_n \bar{l}_\theta$ in the decomposition of $M_n(\theta) - M_n(\bar{\theta}_n)$. For $\theta \in \mathcal{N}$, $\mathbb{E}h^{2q} l_\theta^2(Z_i, Z_j) = \mathbb{E}\left[\left(g'_n(Z_i, \theta) g_n(Z_j, \theta) - g'_n(Z_i, \bar{\theta}_n) g_n(Z_j, \bar{\theta}_n)\right) K\left(\left(X_i - X_j\right)/h\right)\right]^2$. Since $K(\cdot)$ is bounded, the Z_i are independent, and for any $a_1, ..., a_r \in \mathbb{R}$, $(a_1 + ... + a_r)^2 \leq r(a_1^2 + ... + a_r^2)$, deduce that $\mathbb{E}h^{2q} l_\theta^2(Z_i, Z_j) = O(\|\theta - \bar{\theta}_n\|)$. From Assumption M4–(iii), $h^q l_\theta(Z_i, Z_j)$ is Euclidean for an integrable envelope with fourth moment. Use Lemma 7.1 to deduce that for any $0 < \alpha < 1$

$$
\sup_{h>0} |U_n h^q \bar{l}_\theta| = \|\theta - \bar{\theta}_n\|^{\alpha/2} O_p(n^{-1}) + O_p(n^{-1-\alpha/4})
$$

uniformly over $o_p(1)$ neighborhoods of $\bar{\theta}_n$, which yields

$$
\sup_{h \in \mathcal{H}_n} |U_n \bar{l}_\theta| = \|\theta - \bar{\theta}_n\|^{\alpha/2} O_p\left(\sup_{h \in \mathcal{H}_n} n^{-1} h^{-q}\right) + O_p\left(\sup_{h \in \mathcal{H}_n} n^{-1-\alpha/4} h^{-q}\right) . \qquad (7.17)
$$

Choose $\alpha < 1$ such that $nh^{4q/\alpha} \geq C$ for all $h \in \mathcal{H}_n$ from our assumption to deduce that the second term is a $O_p(n^{-1})$. For θ in a $o_p(1)$ neighborhood of $\bar{\theta}_n$, the first term is $O_p(\varepsilon_{0,n})$ with $\varepsilon_{0,n} = o(\sup_{h \in \mathcal{H}_n} n^{-1} h^{-q})$. Use Equations (7.16) and (7.17) in conjunction with Lemma 7.2 to obtain $\|\tilde{\theta}_n - \bar{\theta}_n\| = O_p(\varepsilon_{0n}^{1/2})$. Plug in this result in (7.17), so that the first term is a $O_p(\varepsilon_{1,n})$ with $\varepsilon_{1,n} = \varepsilon_{0,n}^{1+\alpha/4}$. Apply repeatedly m times to get $\varepsilon_{m,n} = \varepsilon_{0,n}^{\alpha_m}$ with $\alpha_m = \sum_{j=0}^{m-1} (\alpha/4)^j$. When m

increases, $\varepsilon_{m,n}$ decreases and α_m tends to $4/(4-\alpha)$. Since $\varepsilon_{0,n}^{4/(4-\alpha)} = o(n^{-1})$, after m iterations with m finite large enough, the first term in Equation (7.17) is a $O_p(n^{-1})$. Apply then again Lemma 7.2 to conclude that $\|\tilde{\theta}_n - \bar{\theta}_n\| = O_p(n^{-1/2})$.

Remark that under Condition 1, Equation (7.17) becomes $\sup_h |U_n \bar{l}_\theta| = \|\theta - \bar{\theta}_n\|^\alpha O_p(\sup_h n^{-1} h^{-q})$. Choose any $\alpha < 1$ such that $nh^{\frac{2q}{\alpha}} \geq C$ for all h and reason as above to obtain that $\sup_h |U_n \bar{l}_\theta| = O_p(n^{-1})$ and $\|\tilde{\theta}_n - \bar{\theta}_n\| = O_p(n^{-1/2})$.

(iii) Asymptotic representation: Equation (7.16) and Part (ii) imply that for any $\alpha \leq \alpha' < 1$, where α comes from our assumptions, $\sup_h |U_n \bar{l}_\theta| = O_p(\sup_h n^{-1-\alpha'/4} h^{-q})$. Conclude that $\sup_h |U_n \bar{l}_\theta| = o_p(n^{-1})$, and use (7.16) to obtain

$$M_n(\theta) = M_n(\bar{\theta}_n) + \frac{1}{2}\,(\theta - \bar{\theta}_n)' \,\bar{V}_n\,(\theta - \bar{\theta}_n) + \frac{1}{\sqrt{n}} A_n'\,(\theta - \bar{\theta}_n) + o_p(1/n)\,, \qquad (7.18)$$

uniformly over $O_p(1/\sqrt{n})$ neighborhoods of $\bar{\theta}_n$ and in $h \in \mathcal{H}_n$. Conclude from Lemma 7.3 that $\sqrt{n}\left(\tilde{\theta}_n - \bar{\theta}_n\right) + \bar{V}_n^{-1} A_n = o_p(1)$.

(iv) Behavior of $\mathbb{G}_n \bar{\phi}_{n,h}$: We consider the case $r = 1$, the multivariate case follows similarly at the cost of more cumbersome algebra. We apply Theorem 19.28 of van der Vaart (1998), where the Lindeberg condition follows from our Assumption M4 and M6. We first consider that $\bar{\theta}_{n,h} = \theta_0$, i.e. a correct model. We have to show his Condition (19.27), that is $\sup_{|h_1 - h_2| < \delta} \mathbb{E}\,\|\phi_{n,h_1}(Z) - \phi_{n,h_2}(Z)\|^2 \to 0$ whenever $\delta \to 0$. Let $\omega_n^2(X, \theta_0) = \mathbb{E}\left[g_n^2(Z, \theta_0)|X\right]$. Proceed as in the consistency proof to show that

$$\begin{aligned}
\mathbb{E}\left[\phi_{n,h_1}'(Z)\phi_{n,h_2}(Z)\right] \quad = \quad & (2\pi)^{q/2} \int_{\mathbb{R}^q}\int_{\mathbb{R}^q} \mathcal{F}\left[\nabla_\theta' \tau_n(\cdot, \theta_0))f(\cdot)\right](-t)\mathcal{F}\left[\omega_n^2(\cdot, \theta_0) f(\cdot)\right](t-u) \\
& \mathcal{F}\left[\nabla_\theta \tau_n(\cdot, \theta_0))f(\cdot)\right](u)\mathcal{F}\left[K\right](h_1 t)\mathcal{F}\left[K\right](h_2 u)\,dt\,du\,.
\end{aligned}$$

Hence, $\quad \mathbb{E}\,\|\phi_{n,h_1}(Z) - \phi_{n,h_2}(Z)\|^2$

$$\begin{aligned}
= \quad & (2\pi)^{q/2} \int_{\mathbb{R}^q}\int_{\mathbb{R}^q} \mathcal{F}\left[\nabla_\theta' \tau_n(\cdot, \theta_0))f(\cdot)\right](-t)\mathcal{F}\left[\omega_n^2(\cdot, \theta_0) f(\cdot)\right](t-u)\mathcal{F}\left[\nabla_\theta \tau_n(\cdot, \theta_0) f(\cdot)\right](u) \\
& \left[\mathcal{F}\left[K\right](h_1 t)\mathcal{F}\left[K\right](h_1 u) - 2\mathcal{F}\left[K\right](h_1 t)\mathcal{F}\left[K\right](h_2 u) + \mathcal{F}\left[K\right](h_2 t)\mathcal{F}\left[K\right](h_2 u)\right]\,dt\,du\,.
\end{aligned}$$

Use the uniform continuity of $\mathcal{F}\left[K\right](\cdot)$, Assumption 4(v)-(vi), the properties of the convolution of Fourier transforms, and the Lebesgue dominated convergence theorem to conclude. The case where $h_2 = 0$ can be treated similarly.

We now turn to the general case of a misspecified model, so we make explicit θ as an argument of $\bar{\phi}_{n,h}$. The result similarly follows if we show $\sup_{|h_1 - h_2| < \delta, \|\theta_1 - \theta_2\| < \delta} \mathbb{E}\,\left\|\bar{\phi}_{n,h_1}(Z, \theta_1) - \bar{\phi}_{n,h_2}(Z, \theta_2)\right\|^2 \to 0$ whenever $\delta \to 0$. When only h varies in this expression, we can apply our previous reasoning, provided we use $\omega_n^2(X, \theta_1, \theta_2) = \mathbb{E}\left[g_n(Z, \theta_1) g_n(Z, \theta_2)|X\right]$ together with Assumption M4. We are left to deal with the case where only θ varies. The result follows from continuity arguments, i.e. Assumptions M4(iv), M5, and M6, and the Lebesgue dominated convergence theorem. $\square$

Proof of Theorem 3.1. Under H_0, $\tilde{\theta}_n^R = R(\tilde{\gamma}_n)$ where $\tilde{\gamma}_n = \arg\min_\gamma M_n(R(\gamma))$. Let $D = \nabla'_\gamma R(\gamma_0)$. From Theorem 2.3's proof, $\sqrt{n}\,(\tilde{\gamma}_n - \gamma_0) = -\left(V_n^R\right)^{-1} B_n + o_p(1)$, where $V_n^R = D'V_nD$ and $B_n = D'A_n$, and

$$
\begin{aligned}
M_n(\tilde{\theta}_n) - M_n(\theta_0) &= \frac{1}{2}\left(\tilde{\theta}_n - \theta_0\right)' V_n \left(\tilde{\theta}_n - \theta_0\right) + \frac{1}{\sqrt{n}} A'_n \left(\tilde{\theta}_n - \theta_0\right) + o_p(1/n) \\
&= -\frac{1}{2n} A'_n V_n^{-1} A_n + o_p(1/n)\,, \\
M_n(R(\tilde{\gamma}_n)) - M_n(R(\gamma_0)) &= \frac{1}{2}\left(\tilde{\gamma}_n - \gamma_0\right)' V_n^R \left(\tilde{\gamma}_n - \gamma_0\right) + \frac{1}{\sqrt{n}} B'_n \left(\tilde{\gamma}_n - \gamma_0\right) + o_p(1/n)\,, \\
&= -\frac{1}{2n} A'_n D \left(D'V_nD\right)^{-1} D'A_n + o_p(1/n) \\
\text{so that} \qquad DM_n &= A'_n V_n^{-1/2} \left[I_p - V_n^{1/2} D \left(D'V_nD\right)^{-1} D' V_n^{1/2}\right] V_n^{-1/2} A_n + o_p(1)
\end{aligned}
$$

uniformly in $h \in \mathcal{H}_n$ under H_0. Our conclusions follows form the extended continuous mapping theorem, see van der Vaart and Wellner (1996, Theorem 1.11.1).

When H_0 does not hold, it follows from the arguments of Theorem 2.1's proof that $M_n(R(\tilde{\gamma}_n)) - M_n(\tilde{\theta}_n)$ converges in probability to a positive constant. $\square$

Proof of Theorem 3.2. Consider $\{(Z_i, w_i)\}$ as the sample and reason as in the proofs of Theorem 2.1 and 2.3, using $\mathbb{E}w^4 < \infty$, to obtain that uniformly in $h \in \mathcal{H}_n$ and over $O_p(1/\sqrt{n})$ neighborhoods of θ_0,

$$
M_n^*(\theta) - M_n^*(\theta_0) = \frac{1}{2}\left(\theta - \theta_0\right)' V_n \left(\theta - \theta_0\right) + \frac{1}{\sqrt{n}} A_n^{*\prime} \left(\theta - \theta_0\right) + o_p(1/n)\,,
$$

where $V_n = \mathrm{H}_{\theta,\theta}\mathbb{E}M_n^*(\theta_0) = \mathrm{H}_{\theta,\theta}\mathbb{E}M_n(\theta_0)$ and A_n^* is the centered empirical process based on

$$
w g'_n(Z,\theta_0)\left[\int_{\mathbb{R}^q} \nabla'_\theta \tau_n(x,\theta_0) f(x) h^{-q} K\left((X-x)/h\right)\, dx\right].
$$

Hence $\sqrt{n}\left(\tilde{\theta}_n^* - \theta_0\right) + V_n^{-1}A_n^* = o_p(1)$ and $\mathbb{P}\left[\sup_{h\in\mathcal{H}_n}\left|\sqrt{n}\left(\tilde{\theta}_n^* - \theta_0\right) + V_n^{-1}A_n^*\right| \geq \varepsilon | Z_1, \ldots Z_n\right] = o_p(1)$ by Markov inequality.

Now, $\sqrt{n}\left(\tilde{\theta}_n^* - \tilde{\theta}_n\right) = -V_n^{-1}\left(A_n^* - A_n\right) + o_p(1)$, where $A_n^* - A_n$ is the centered empirical process based on

$$
(w-1)\, g'_n(Z,\theta_0)\left[\int_{\mathbb{R}^q} \nabla'_\theta \tau_n(x,\theta_0) f(x) h^{-q} K\left((X-x)/h\right)\, dx\right].
$$

It is then clear that the process $A_n^* - A_n$ has asymptotically and conditionally upon the initial sample the same distribution as A_n uniformly in h, see e.g. Zhang (2001), so that $\sqrt{n}\left(\tilde{\theta}_n^* - \tilde{\theta}_n\right)$

has asymptotically and conditionally upon the initial sample the same distribution as $\sqrt{n}\left(\tilde{\theta}_n - \theta_0\right)$ uniformly in h.[7] Therefore, uniformly in $h \in \mathcal{H}_n$,

$$\begin{aligned}
M_n^*(\tilde{\theta}_n^*) - M_n^*(\theta_0) &= -\frac{1}{2}\left(\tilde{\theta}_n^* - \theta_0\right)' V_n \left(\tilde{\theta}_n^* - \theta_0\right) + o_p(1/n)\,, \\
M_n^*(\tilde{\theta}_n) - M_n^*(\theta_0) &= \frac{1}{2}\left(\tilde{\theta}_n - \theta_0\right)' V_n \left(\tilde{\theta}_n - \theta_0\right) - \left(\tilde{\theta}_n^* - \theta_0\right)' V_n \left(\tilde{\theta}_n - \theta_0\right) + o_p(1/n)\,, \\
\text{and } n\left[M_n^*(\tilde{\theta}_n^*) - M_n^*(\tilde{\theta}_n)\right] &= -\frac{1}{2}\sqrt{n}\left(\tilde{\theta}_n^* - \tilde{\theta}_n\right)' V_n \sqrt{n}\left(\tilde{\theta}_n^* - \tilde{\theta}_n\right) + o_p(1) \\
&= -\frac{1}{2}\left(A_n^* - A_n\right)' V_n^{-1}\left(A_n^* - A_n\right) + o_p(1)\,.
\end{aligned}$$

As before, this expansion also holds conditionally. Therefore, the latter process has asymptotically and conditionally upon the initial sample the same distribution as $n\left[M_n(\tilde{\theta}_n) - M_n(\theta_0)\right]$. □

Proof of Theorem 3.3. Theorem 3.2's proof deals with the unconstrained problem. A similar reasoning applies to the constrained problem. Proceed as in Theorem 3.1's proof to conclude that DM_n^* has asymptotically and conditionally upon the initial sample the same distribution as DM_n under H_0 uniformly in $h \in \mathcal{H}_n$.

When H_0 does not hold, it follows from Theorem 2.1's proof that $M_n^*(\tilde{\theta}_n^*) - M_n^*(\tilde{\theta}_n) = o_p(1)$ and similarly $M_n^*\left(R(\tilde{\gamma}_n^*)\right) - M_n^*\left(R(\tilde{\gamma}_n)\right) = o_p(1)$, so that $DM_n^* = o_p(n)$ uniformly in $h \in \mathcal{H}_n$. □

Proof of Corollary 4.1. Under our assumptions, $\tilde{\theta}_{n,h}$ is asymptotically $N(0, V_0^{-1}\Delta_{0,0}V_0^{-1})$ uniformly over $h \in \mathcal{H}_n'$ where

$$V_0 = \mathbb{E}\left[\nabla_\theta \mathbb{E}\left[g(Z,\theta_0)|X\right] W^{-1}(X) \nabla_\theta' \mathbb{E}\left[g(Z,\theta_0)|X\right] f(X)\right] \quad \text{and}$$

$$\Delta_{0,0} = \mathbb{E}\left[\nabla_\theta \mathbb{E}\left[g(Z,\theta_0)|X\right] W^{-1}(X) \mathrm{Var}\left[g(Z,\theta_0)|X\right] W^{-1}(X) \nabla_\theta' \mathbb{E}\left[g(Z,\theta_0)|X\right] f^2(X)\right].$$

Plug $W(X) = \mathrm{Var}\left[g(Z,\theta_0)|X\right] f(X)$ to obtain the result. □

Proof of Theorem 4.2. Step 1 is to obtain the uniform rate of convergence of $\widehat{W}_n(\cdot,\theta) - W_n(\cdot,\theta)$, where $W_n(\cdot,\theta) = \mathbb{E}\left[\widehat{W}_n(\cdot,\theta)\right]$. A useful result can be derived along the lines of Proposition 2 of Einmahl and Mason (2005). A careful inspection of their proof shows that the result holds not only on a compact subset, but on the whole space $\mathbb{R}^q$ provided their Condition (1.7) on the continuity of the density $f(\cdot)$ is replaced by the assumption of a bounded density.

[7] Zhang (2001) assumes that w has an exponential distribution, but uses only moment conditions. It is easily seen that our assumptions on w are sufficient.

Lemma 7.4. *Let Φ denote a class of measurable functions on $\mathbb{R}^{d+q}$, where $d, q \geq 1$, with a finite-valued measurable envelope function F. Further assume that the kernel $L(\cdot)$ is a density of bounded variation with bounded support, the density $f(\cdot)$ is bounded and*

$$\sup_{x \in \mathbb{R}^q} \mathbb{E}[F^4(Z) \mid X = x] < \infty.$$

Let $\eta_{\varphi,n,b}(x) = (nb^q)^{-1} \sum_{1 \leq i \leq n} \varphi(Z_i) L((x - X_i)/b), \quad \varphi \in \Phi$ and $\|\cdot\|_\infty$ be the supremum norm. There exists $c > 0$ such that, with probability 1

$$\limsup_{n \to \infty} \sup_{b \in \mathcal{H}_n} \sqrt{nb^q} \, \frac{\sup_{\varphi \in \Phi} \|\eta_{\varphi,n,b} - \mathbb{E}\eta_{\varphi,n,b}\|_\infty}{\sqrt{\ln(1/b^q) \vee \ln \ln n}} = c\,.$$

Step 2 consists in establishing an expansion of the power $-1/2$ of a positive definite matrix. By the integral representation of the square root of a matrix, see e.g. Higham (2008), for any positive definite $q \times q$ matrix A

$$A^{-1/2} = \frac{2}{\pi} \int_0^\infty \left(t^2 A + I\right)^{-1} dt.$$

Moreover, for any conformable square matrices B and D and any $t > 0$,

$$\begin{aligned}
(A + B)^{-1} \quad &= \quad A^{-1} - A^{-1}\left(I + BA^{-1}\right)^{-1} BA^{-1}\,, && (7.19)\\
\text{and} \qquad \left[I + t^2 D \left(t^2 A + I\right)^{-1}\right]^{-1} \quad &= \quad I - t^2 D \left(t^2 A + I\right)^{-1} + R\,, \\
\text{with} \qquad \|R\| \leq \sqrt{q}\, \|R\|_2 \quad &\leq \quad \frac{\sqrt{q} \left\| t^2 D \left(t^2 A + I\right)^{-1} \right\|_2^2}{1 - \left\| t^2 D \left(t^2 A + I\right)^{-1} \right\|_2} \\
&\leq \quad \sqrt{q}\, \|D\|_2^2 \left[\frac{t^2}{1 + t^2 \lambda_{min}(A)}\right]^2 \left[1 - \frac{t^2 \|D\|_2}{1 + t^2 \lambda_{min}(A)}\right]^{-1} \\
&\leq \quad k(c) \|D\|_2^2 \leq k(c) \|D\|^2\,.
\end{aligned}$$

Here and in what follows, $\|\cdot\|_2$ denotes the spectral matrix norm, $\lambda_{min}(A)$ is as before the smallest eigenvalue of A, and $k(c)$ depends on c, $\lambda_{\min}(A)$, and $\sqrt{q}$, where c is assumed to be such that

$$\|D\|_2 / \lambda_{min}(A) \leq \|D\| / \lambda_{min}(A) \leq c < 1\,.$$

Use the integral representation for $(A + D)^{-1/2}$ and $A^{-1/2}$ and apply (7.19) with A replaced by $t^2 A + I$ and $B = t^2 D$ to deduce that

$$\begin{aligned}
(A + D)^{-1/2} - A^{-1/2} \quad = \quad &- \frac{2}{\pi} \int_0^\infty t^2 \left(t^2 A + I\right)^{-1} D \left(t^2 A + I\right)^{-1} dt \\
&+ \frac{2}{\pi} \int_0^\infty t^4 \left(t^2 A + I\right)^{-1} D \left(t^2 A + I\right)^{-1} D \left(t^2 A + I\right)^{-1} dt \\
&- \frac{2}{\pi} \int_0^\infty t^2 \left(t^2 A + I\right)^{-1} RD \left(t^2 A + I\right)^{-1} dt\,, \qquad (7.20)
\end{aligned}$$

$$\text{where } \left\| \left(t^2 A + I\right)^{-1} RD \left(t^2 A + I\right)^{-1} \right\| \leq \left[\frac{1}{1 + t^2 \lambda_{min}(A)} \right]^2 k(c) \|D\|^3 .$$

This implies that for some constant C the last integral in (7.20) is bounded by

$$\frac{2}{\pi} k(c) \|D\|^3 \int_0^\infty t^2 \left[1 + t^2 \lambda_{min}(A)\right]^{-2} dt \leq C \|D\|^3 .$$

Step 3 consists in applying Identity (7.20) to our problem, with $D = D_{n,i}(\theta_2) = \widehat{W}_n(X_i, \theta_2) - W_n(X_i, \theta_0)$ and $A = W_n(X_i, \theta_0) = W_n(X_i)$. Let $\widehat{M}_n(\theta, \theta_2)$ and $M_n(\theta)$ be the objective functions with weighting matrix $\widehat{W}_n(\cdot, \theta_2)$ and $W_n(\cdot)$, respectively. Let also $0 < \lambda \leq \inf_{x,n} \lambda_{\min}(W_n(x))$ for some fixed $\lambda > 0$, which exists by our Assumption E7. For any $\theta \in \Theta$ and θ_2 in a $O(n^{-1/2})$ neighborhood of θ_0,

$$\begin{aligned}
\widehat{M}_n(\theta, \theta_2) &= M_n(\theta) - \frac{2}{\pi} \int_0^\infty t^2 \left[1 + t^2 \lambda\right]^{-2} \left[M_{1n}(t) + M'_{1n}(t)\right] dt \\
&\quad + \frac{2}{\pi} \int_0^\infty t^4 \left[1 + t^2 \lambda\right]^{-3} \left[M_{2n}(t) + M'_{2n}(t)\right] dt \\
&\quad + \frac{4}{\pi^2} \int_0^\infty \int_0^\infty t^2 \left[1 + t^2 \lambda\right]^{-2} s^2 \left[1 + s^2 \lambda\right]^{-2} M_{3n}(t, s) \, dt \, ds \\
&\quad + O_p\left(\sup_{x \in \mathbb{R}^q} \sup_{\|\theta_2 - \theta_0\| \leq C n^{-1/2}} \sup_{b \in \mathcal{H}'_n} \left\| \widehat{W}_n(x, \theta_2) - \widehat{W}_n(x) \right\|^3 \right) .
\end{aligned}$$

The last term is an $o_p(n^{-1})$ uniformly in $b \in \mathcal{H}'_n$ by Step 1 and noticing that from Assumption E7, for some $C > 0$ and $\nu > 2/3$, $\|\mathbb{E}\left[\left(\omega^2(X, \theta_2) - \omega^2(X, \theta_0)\right) b^{-q} L((X - x)/b)\right]\| \leq c\|\theta_2 - \theta_0\|^\nu \|\mathbb{E}\left[b^{-q} L((X - x)/b)\right]\| \leq C\|\theta_2 - \theta_0\|^\nu = o(n^{-1/3})$ uniformly in θ_2 in a $O(n^{-1/2})$ neighborhood of θ_0. In the last display,

$$\begin{aligned}
M_{1n}(t) &= M_{1n}(t, \theta, \theta_2, h, b) \\
&= \frac{t^{-4}\left(1 + t^2 \lambda\right)^2}{2n(n-1)} \sum_{i \neq j} g'(Z_i, \theta)[W_n(X_i) + t^{-2} I]^{-1} D_{n,i}(\theta_2) \\
&\qquad \times [W_n(X_i) + t^{-2} I]^{-1} W_n^{-1/2}(X_j) g(Z_j, \theta) K_{ij} , \\
M_{2n}(t) &= M_{2n}(t, \theta, \theta_2, h, b) \\
&= \frac{t^{-6}\left(1 + t^2 \lambda\right)^3}{2n(n-1)} \sum_{i \neq j} g'(Z_i, \theta)[W_n(X_i) + t^{-2} I]^{-1} D_{n,i}(\theta_2)[W_n(X_i) + t^{-2} I]^{-1} \\
&\qquad \times D_{n,i}(\theta_2)[W_n(X_i) + t^{-2} I]^{-1} W_n^{-1/2}(X_j) g(Z_j, \theta) K_{ij} ,
\end{aligned}$$

$$\begin{aligned}
M_{3n}(t, s) &= M_{3n}(t, s, \theta, \theta_2, h, b) \\
&= \frac{(1 + t^2 \lambda)^2 (1 + s^2 \lambda)^2}{t^4 s^4 2n(n-1)} \sum_{i \neq j} g'(Z_i, \theta)[W_n(X_i) + t^{-2} I]^{-1} D_{n,i}(\theta_2)[W_n(X_i) + t^{-2} I]^{-1} \\
&\qquad \times [W_n(X_j) + s^{-2} I]^{-1} D_{n,j}(\theta_2)[W_n(X_j) + s^{-2} I]^{-1} g(Z_j, \theta) K_{ij} .
\end{aligned}$$

Strictly speaking, we should separate the integrals on $[0,1)$ and $[1,\infty)$ in the following. Specifically, for $t \in [0,1)$, the terms $\left[W_n(\cdot)+t^{-2}I\right]^{-1}$ should be replaced by $\left[t^2 W_n(\cdot)+I\right]^{-1}$, with adequate changes in the other arguments under the integral. The following arguments adapt easily.

Step 4 is to show that uniformly over θ in a $o(1)$ neighborhood of θ_0 and θ_2 in a $O(n^{-1/2})$ neighborhoods of θ_0

$$\sup_{t,s\geq 1}\sup_{b,h\in\mathcal{H}_n}\left\{\|M_{1n}\|+\|M_{2n}\|+\|M_{3n}\|\right\} = o_p\left(n^{-1}+\|\theta-\theta_0\|/\sqrt{n}+\|\theta-\theta_0\|^2\right), \tag{7.21}$$

which implies (4.8). The terms M_{1n}, M_{2n} and M_{3n} involve the family of matrix-valued functions

$$\left\{\left[W_n(\cdot)+t^{-2}I\right]^{-1} : b\in\mathcal{H}_n',\, t\geq 1\right\} \quad \text{and} \quad \left\{W_n^{-1/2}(\cdot) : b\in\mathcal{H}_n'\right\}.$$

For $t\in[0,1)$, the first family has to be replaced by $\left\{\left[t^2 W_n(\cdot)+I\right]^{-1} : b\in\mathcal{H}_n',\, t\in[0,1)\right\}$. We here focus on the case $t\geq 1$, the arguments for the other case being similar. Lemma 7.8 in Appendix B shows that under our assumptions these families of functions are Euclidean entrywise for a constant envelope. For the sake of simplicity, we show (7.21) only for $r=1$, since the same arguments apply componentwise for $r>1$ at the expense of much more cumbersome algebra. Also we focus on $M_{1n}(t)$, since a similar reasoning applies to $M_{2n}(t)$ and $M_{3n}(t)$. Let

$$\begin{aligned} d_{\theta_2}(x,Z_k) &= g^2(Z_k,\theta_2)\,L\left((x-X_k)/b\right) - \mathbb{E}\left[\omega^2(X,\theta_2)L\left((x-X)/b\right)\right], \\ \delta_{\theta_2}(x) &= \mathbb{E}\left[\omega^2(X,\theta_2)L\left((x-X)/b\right)\right] - \mathbb{E}\left[\omega^2(X,\theta_0)L\left((x-X)/b\right)\right], \end{aligned}$$

so that $D_{n,i}(\theta_2) = \frac{1}{nb^q}\sum_{1\leq k\leq n}\left[d_{\theta_2}(X_i,Z_k)+\delta_{\theta_2}(X_i)\right]$. We accordingly separate $M_{1n}(t)$ into two terms and we study each of them in turn.

Note that $\mathbb{E}\left[d_{\theta_2}(X_i,Z_k)\,|X_i\right]=0$ for $i\neq k$ and consider the decomposition

$$\begin{aligned} &\frac{1}{nb^q}\frac{1}{(n)_2}\sum_{1\leq k\leq n}\sum_{i\neq j}\frac{g(Z_i,\theta)}{\left[W_n(X_i)+t^{-2}\right]^2}d_{\theta_2}(X_i,Z_k)\,W_n^{-1/2}(X_j)g(Z_j,\theta)K_{ij} \\ =\;& \frac{(n-2)}{nb^q}\frac{1}{(n)_3}\sum_{i\neq j\neq k}\frac{g(Z_i,\theta)}{\left[W_n(X_i)+t^{-2}\right]^2}\,d_{\theta_2}(X_i,Z_k)\,W_n^{-1/2}(X_j)g(Z_j,\theta)K_{ij} \\ &+\frac{1}{nb^q}\frac{1}{(n)_2}\sum_{i\neq j}\frac{g(Z_i,\theta)}{\left[W_n(X_i)+t^{-2}\right]^2}\,d_{\theta_2}(X_i,Z_i)\,W_n^{-1/2}(X_j)g(Z_j,\theta)K_{ij} \\ &+\frac{1}{nb^q}\frac{1}{(n)_2}\sum_{i\neq j}\frac{g(Z_i,\theta)}{\left[W_n(X_i)+t^{-2}\right]^2}\,d_{\theta_2}(X_i,Z_j)\,W_n^{-1/2}(X_j)g(Z_j,\theta)K_{ij} \\ =\;& \frac{(n-2)}{nb^qh^q}\frac{1}{(n)_3}\sum_{i\neq j\neq k}m_{11}(Z_i,Z_j,Z_k)+\frac{1}{nb^qh^q}\frac{1}{(n)_2}\sum_{i\neq j}m_{12}(Z_i,Z_j) \\ &+\frac{1}{nb^qh^q}\frac{1}{(n)_2}\sum_{i\neq j}m_{13}(Z_i,Z_j) \\ =\;& \frac{(n-2)}{nb^qh^q}M_{11n}+\frac{1}{nb^qh^q}M_{12n}+\frac{1}{nb^qh^q}M_{13n}, \end{aligned}$$

where $(n)_k = n!/(n-k)!$. For the first and dominant term, write

$$
\begin{aligned}
m_{11} = m_{11}\left(Z_i, Z_j, Z_k\right) &= \frac{g(Z_i,\theta_0)}{\left[W_n(X_i)+t^{-2}\right]^2}\, d_{\theta_2}\left(X_i, Z_k\right) W_n^{-1/2}(X_j) g(Z_j,\theta_0) h^q K_{ij} \\
+ & \quad \frac{g(Z_i,\theta_0)}{\left[W_n(X_i)+t^{-2}\right]^2}\, d_{\theta_2}\left(X_i, Z_k\right) W_n^{-1/2}(X_j)\left\{g(Z_j,\theta) - g(Z_j,\theta_0)\right\} h^q K_{ij} \\
+ & \quad \frac{\left\{g(Z_i,\theta) - g(Z_i,\theta_0)\right\}}{\left[W_n(X_i)+t^{-2}\right]^2}\, d_{\theta_2}\left(X_i, Z_k\right) W_n^{-1/2}(X_j) g(Z_j,\theta_0) h^q K_{ij} \\
+ & \quad \frac{\left\{g(Z_i,\theta) - g(Z_i,\theta_0)\right\}}{\left[W_n(X_i)+t^{-2}\right]^2}\, d_{\theta_2}\left(X_i, Z_k\right) W_n^{-1/2}(X_j)\left\{g(Z_j,\theta) - g(Z_j,\theta_0)\right\} h^q K_{ij} \\
= & \quad m_{110} + m_{111} + m_{112} + m_{113}.
\end{aligned}
$$

We note that our assumptions ensure that all functions entering the above terms, as indexed by θ, θ_2, h, and b, are Euclidean. In particular Appendix B shows that the class of functions $x \mapsto W_n^{-1/2}(x)$ is Euclidean as indexed by b for a constant envelope by Assumption E7-(iii).

By convention, for $j = 0, \ldots 3$, we denote by M_{11jn} the U-process based on m_{11j}. The term M_{110n} is a third-order degenerate U-process independent of θ and is a $O_p(n^{-3/2})$ uniformly in θ_2, h, b, and t. Consider the Hoeffding's decomposition of M_{111n} and note that $\mathbb{E}[m_{111} \mid Z_i, Z_j] = \mathbb{E}[m_{111} \mid Z_j, Z_k] = 0$. The third order degenerate U-process in that decomposition is a uniform $o_p(n^{-3/2})$ by Corollary 8 of Sherman (1994a). The remaining term to be studied is the degenerate second order U-process defined by the family of functions

$$
\frac{g(Z_i,\theta_0) d_{\theta_2}\left(X_i, Z_k\right)}{\left[W_n(X_i)+t^{-2}\right]^2} \mathbb{E}\left[W_n^{-1/2}(X_j)\left\{g(Z_j,\theta) - g(Z_j,\theta_0)\right\} h^q K_{ij} \mid X_i\right].
$$

By a Taylor expansion of $\mathbb{E}\left[g(Z_j,\theta_0)|X_j\right]$ around θ_0 and Assumption E7, deduce that the uniform rate of convergence of this U-process is $O_p(n^{-1}\|\theta-\theta_0\|)$. Similar arguments apply to $h^q M_{112n}$. For M_{113n}, the different terms in Hoeffding's decomposition are the third order degenerate U-process, the two degenerate second order U-processes based on $\mathbb{E}[m_{113} \mid Z_j, Z_k] - \mathbb{E}[m_{113} \mid Z_k]$ and $\mathbb{E}[m_{113} \mid Z_i, Z_k] - \mathbb{E}[m_{113} \mid Z_k]$, and the empirical process based on $\mathbb{E}[m_{113} \mid Z_k]$. For the third and second order U-processes we proceed as above. For the remaining (centered) empirical process, rely again on Taylor expansions around θ to deduce that its uniform rate of convergence is $O_p(n^{-1/2}\|\theta-\theta_0\|^2)$. Gathering these facts and using $n^{-1}\{\inf \mathcal{H}_n'\}^{-4q} = o_p(1)$ show that

$$
\sup_{t\geq 1} \sup_{h,b\in\mathcal{H}_n'} \left|b^{-q}h^{-q} M_{11n}\right| = o_p\left(\|\theta-\theta_0\|\, n^{-1/2} + \|\theta-\theta_0\|^2 + n^{-1}\right)
$$

uniformly over θ and θ_2 in $o(1)$ neighborhoods of θ_0. For $n^{-1}b^{-q}M_{12n}$ and $n^{-1}b^{-q}M_{13n}$, follow a similar (shorter) reasoning to obtain the same order.

Recall that $\|\delta_{\theta_2}(X_i)\| \leq c\|\theta_2 - \theta_0\|^\nu$ for some $\nu > 2/3$ and $c > 0$ uniformly in b and $\theta_2 - \theta_0 = O_p(n^{-1/2})$, and note that

$$
\begin{aligned}
&\frac{1}{b^q}\frac{1}{(n)_2}\sum_{1\leq k\leq n}\sum_{i\neq j}\frac{g(Z_i,\theta)}{[W_n(X_i)+t^{-2}]^2}\delta_{\theta_2}(X_i)\,W_n^{-1/2}(X_j)g(Z_j,\theta)K_{ij}\\
&= \frac{1}{b^q}\frac{1}{(n)_2}\sum_{i\neq j}\frac{g(Z_i,\theta_0)}{[W_n(X_i)+t^{-2}]^2}\,\delta_{\theta_2}(X_i)\,W_n^{-1/2}(X_j)g(Z_j,\theta_0)K_{ij}\\
&+ \frac{1}{b^q}\frac{1}{(n)_2}\sum_{i\neq j}\frac{g(Z_i,\theta_0)}{[W_n(X_i)+t^{-2}]^2}\,\delta_{\theta_2}(X_i)\,W_n^{-1/2}(X_j)\left\{g(Z_j,\theta)-g(Z_j,\theta_0)\right\}K_{ij}\\
&+ \frac{1}{b^q}\frac{1}{(n)_2}\sum_{i\neq j}\frac{\{g(Z_i,\theta)-g(Z_i,\theta_0)\}}{[W_n(X_i)+t^{-2}]^2}\,\delta_{\theta_2}(X_i)\,W_n^{-1/2}(X_j)g(Z_j,\theta_0)K_{ij}\\
&+ \frac{1}{b^q}\frac{1}{(n)_2}\sum_{i\neq j}\frac{\{g(Z_i,\theta)-g(Z_i,\theta_0)\}}{[W_n(X_i)+t^{-2}]^2}\,\delta_{\theta_2}(X_i)\,W_n^{-1/2}(X_j)\left\{g(Z_j,\theta)-g(Z_j,\theta_0)\right\}K_{ij}\\
&= b^{-q}h^{-q}\left(\tilde{M}_{10n}+\tilde{M}_{11n}+\tilde{M}_{12n}+\tilde{M}_{13n}\right).
\end{aligned}
$$

Use Hoeffding's decomposition and the last statement of Lemma 7.1 to deduce that $\tilde{M}_{10n}$ is a uniform $O_p(n^{-1-2\alpha/3})$ for any $\alpha < 1$. Use a Taylor expansion around θ_0, Hoeffding's decomposition, and Lemma 7.1 to show that each of $\tilde{M}_{1jn}$, $j = 1, 2$, is a $O_p\left(\|\theta-\theta_0\|n^{-1/2-2\alpha/3}\right)$ for any $\alpha < 1$. Use similar arguments to show that $\tilde{M}_{13n} = O_p\left(\|\theta-\theta_0\|^2 n^{-2\alpha/3}\right)$ for any $\alpha < 1$. Gathering these facts and using $n^{-1}\{\inf \mathcal{H}_n'\}^{-4q/\alpha} = o_p(1)$ for some $\alpha < 1$,

$$
\sup_{t\geq 1}\sup_{h,b\in\mathcal{H}_n'}\left|b^{-q}M_{1n}\right| = o_p\left(\|\theta-\theta_0\|\,n^{-1/2}+\|\theta-\theta_0\|^2+n^{-1}\right)
$$

uniformly over θ in a $o(1)$ neighborhoods of θ_0 and θ_2 in a $O_p(n^{-1/2})$ neighborhood of θ_0. □

Proof of Corollary 4.3. Assumption E6, Lemma 7.6 of Appendix A, and Lemma 7.8 of Appendix B ensure that the class of functions $(x,u) \mapsto W_n^{-1/2}(x-hu)\nabla_\theta\tau(x-hu,\theta_0)f(x-hu)$ is Euclidean entrywise for a constant envelope, so that

$$
\{x \mapsto \int W_n^{-1/2}(x-hu)\nabla_\theta\tau(x-hu,\theta_0)f(x-hu)K(u)du : h, b\in[0,h_0]\}
$$

is uniformly Euclidean for a constant envelope by Nolan and Pollard (1987, Lemma 20). Reason similarly for the functions $W_n^{-1/2}(\cdot)\mathrm{H}_{\theta,\theta}\tau_n^{(k)}(\cdot,\theta_0)f(\cdot)$, $1\leq k\leq r$ and $W_n^{-1/2}(\cdot H(\cdot)f(\cdot)$. Use Lemmas 7.2 and 7.3 in Section 7.1 and Equation (4.8) to obtain an asymptotic representation similar to the one of Theorem 2.3. □

Appendix A

We focus here on providing sets of sufficient conditions that guarantee Condition (E). We note that since $\int \phi_n(x-uh)K(u)du$ is the expectation of a kernel estimator, our subsequent results are of independent interest.

Lemma 7.5. *Assume that $K(\cdot)$ is integrable and its Fourier transform $\mathcal{F}[K](\cdot)$ is Hölder continuous with exponent a. If the sequence of functions $\phi_n : \mathbb{R}^q \to \mathbb{R}$, $n \geq 1$ have integrable envelope $\Phi(\cdot)$, they satisfy Condition (E) with kernel $K(\cdot)$ for an envelope $\Phi(\cdot) + C$, $C > 0$, whenever*

$$\sup_n \int \|t\|^a \left|\mathcal{F}[\phi_n](t)\right| dt < \infty. \tag{7.22}$$

Proof. For any ϕ_n, write

$$\begin{aligned}\int \phi_n(x-hu)K(u)du &= (2\pi)^{-q/2} \int\int \phi_n(v)\exp(it'(x-v))\mathcal{F}[K](ht)dvdt \\ &= \int \mathcal{F}[\phi_n](t)\exp(it'x)\mathcal{F}[K](ht)dt\,,\end{aligned}$$

for almost any x, and note that the equality holds trivially for $h = 0$. Hence for any $h_1, h_2 \in [0, h_0]$, using $|\mathcal{F}[K](t_1) - \mathcal{F}[K](t_2)| \leq c\|t_1 - t_2\|^a$,

$$\begin{aligned}\left|\int \phi_n(x-h_1u)K(u)du - \int \phi_n(x-h_2u)K(u)du\right| &\leq \int \left|\mathcal{F}[\phi_n](t)\right| \left|\mathcal{F}[K](h_1t) - \mathcal{F}[K](h_2t)\right| dt \\ &\leq c|h_1-h_2|^a \int \|t\|^a \left|\mathcal{F}[\phi_n](t)\right| dt\,.\end{aligned}$$

Use Lemma 2.13 of Pakes and Pollard (1989) to conclude. □

As most common kernels have bounded moment of order 1, the Hölder continuity of $\mathcal{F}[K](\cdot)$ is satisfied with $a = 1$, so we assume this from now on without much loss of generality. Condition (7.22) is fulfilled when $\phi_n(\cdot)$ belongs to $W^{m,1}$, the subspace of functions of L^1 such that their weak partial derivatives belongs to L^1 up to integer order $m \geq 3$, see e.g. Malliavin (1995, Section III.3). Another possible space is the Sobolev space of functions H^s. Indeed,

$$\int \|t\| \left|\mathcal{F}[\phi_n](t)\right| dt \leq \int_{\|t\|\leq 1} \left|\mathcal{F}[\phi_n](t)\right| dt + \int_{\|t\|>1} \|t\| \left|\mathcal{F}[\phi_n](t)\right| dt = \int \Phi(x)dx + I_2\,.$$

By Cauchy-Schwarz inequality, for any $b > 1$

$$I_2 \leq \left[\int \left(1 + \|t\|^2\right)^{1+b/2} \left|\mathcal{F}[\phi_n](t)\right|^2 dt\right]^{1/2} \left[\int_{\|t\|>1} \|t\|^{-b}\, dt\right]^{1/2}.$$

Condition (7.22) then holds for a sequence $\phi_n(\cdot)$ from the Sobolev space of functions H^s with $s > 3/2$ endowed with the norm

$$\|\phi\|_{H^s}^2 = \int_{\mathbb{R}^d} \left(1 + \|t\|^2\right)^s \left|\mathcal{F}[\phi](t)\right|^2 dt.$$

For any integer $s \geq 1$, H^s is isomorph to $W^{s,2}$ endowed with the norm $\|\phi\|^2_{W^{s,2}} = \sum_{0\leq|\alpha|\leq s} \|D^\alpha\phi\|^2_{L^2}$, where for a multi-index $\alpha = (\alpha_1, ..., \alpha_q)$ of degree $|\alpha| = \alpha_1 + ... + \alpha_q$, $D^\alpha\phi$ denotes the weak partial derivative of ϕ, see Malliavin (1995, Section III.3) or Adams and Fournier (2003, Chapter 3). Finally, we note that if two sequences of functions belongs to $W^{m,2}$ with $m \geq 3$, their product belongs to $W^{m,1}$ and thus also fulfills Condition (E).
Different sufficient conditions are provided in the next lemma.

Lemma 7.6. *For $K(\cdot)$ integrable, any of the following conditions ensures that Condition (E) holds for a constant envelope.*

i. *$\phi_n(x) = \psi_n(p(x))$, where $p(x)$ is a polynomial in q variables and $\psi_n(\cdot)$ is a uniformly bounded sequence of functions of bounded variation on $\mathbb{R}$.*

ii. *The functions $\phi_n(\cdot)$ are uniformly bounded and Hölder continuous with exponent a, and $\int \|u\|^a |K(u)|du < \infty$.*

iii. *The functions ϕ_n are finite addition, multiplication,* min*, or* max *of functions satisfying one of (i) or (ii) (for finite multiplication under (ii), assume that $K(\cdot)$ has enough finite moments).*

Proof. The proof follows by showing in each case that $\{(x, u) \mapsto \phi_n(x-hu) : h \in [0, 1]\}$ is Euclidean for a constant envelope and using that the Euclidean property is preserved by integration with respect to a finite measure, see Nolan and Pollard (1987, Lemma 20).
(i) For each n, the class of subgraphs $\{(x, u) \mapsto subgraph(\phi_n(x - uh)) : h \in [0, 1]\}$ is a VC class of sets by the arguments of Lemma 22 of Nolan and Pollard (1987). A careful inspection of their proof shows that the index of this class of subgraphs is independent on n provided the functions ϕ_n are uniformly bounded, and the class of functions is thus Euclidean.
(ii) As for all n, $|\phi_n(x_1) - \phi_n(x_2)| \leq c\|x_1 - x_2\|^a$ for some $c > 0$, $|\phi_n(x - uh_1) - \phi_n(x - uh_2)| \leq c\|u\|^a|h_1 - h_2|^a$. Lemma 2.13 of Pakes and Pollard (1989) thus implies that the class of $\phi_n(x - hu)$ as functions of (x, u) is Euclidean for an envelope $C_1 + C_2\|u\|^a$ for some $C_1, C_2 > 0$.
(iii) From the above proofs, each of the class of functions $\phi_n(x, u; h) = \phi_n(x - hu)$ as functions of (x, u) is Euclidean for a constant envelope in Case (i), for an integrable envelope in Case (ii). From Lemma 2.14 of Pakes and Pollard (1989), finite additions, multiplications, maximum, and minimum, of functions in such families are Euclidean with an envelope deduced by similar operations on the envelopes of each family. □

Since the indicator function $\mathbb{I}(u \geq 0)$ is of bounded variation on $\mathbb{R}$, Lemma 7.6-(i) implies that Condition (E) is satisfied when $\phi_n(\cdot) = \phi(\cdot) = \mathbb{I}(p(x) \geq 0)$ for any polynomial $p(x)$. Hence, $\phi(\cdot)$ can be the indicator function of a half space, a ball, a rectangle, or finite unions and intersections of such subsets of $\mathbb{R}^q$. Now, if the $\phi_n(\cdot)$ have a common fixed bounded support (and vanish outside this set) and the Hölder continuity condition in Lemma 7.6-(ii) holds on this support, then $\phi_n(\cdot)$ can always be written as the product of the indicator function of the support and a Hölder continuous extension of $\phi_n(\cdot)$ to the whole space $\mathbb{R}^q$, which exists by the McShane-Whitney theorem, see McShane (1934). Lemma 7.6-(iii) then ensures that the $\phi_n(\cdot)$ satisfy Condition (E).

Appendix B

We provide here useful lemmas for proving that the primitive assumptions on the conditional variance of $g(Z,\theta_0)$ are sufficient for our results from Section 4 to hold.

Lemma 7.7. *Let $\omega(x;b)$, $b\in[0,h_0]$, be positive definite $r\times r$ matrix-valued functions on $\mathbb{R}^q$ with eigenvalues uniformly bounded away from zero and infinity. If $\{(x,u)\mapsto\omega(x-uh;b):h,b\in[0,h_0]\}$ is Euclidean for a constant envelope, then $\{(x,u)\mapsto\omega^{-s}(x-uh;b):h,b\in[0,h_0]\}$, $s=1/2$ or 1, is Euclidean for a constant envelope.*

Proof. We treat the case $s=1/2$, the other case similarly follows. For any p.d. A and B, and the spectral matrix norm $\|\cdot\|_2$,

$$\left\|A^{1/2}-B^{1/2}\right\|_2\leq\frac{1}{2}\left\{\max\left(\left\|A^{-1}\right\|_2,\left\|B^{-1}\right\|_2\right)\right\}^{1/2}\|A-B\|_2\ ,$$

see Horn and Johnson (1991, page 557). Since $A^{-1}-B^{-1}=A^{-1}(B-A)B^{-1}$,

$$\begin{aligned}\|A^{-1}-B^{-1}\|_2&\leq\|A^{-1}\|_2\|B-A\|_2\|B^{-1}\|_2\\ \text{and}\quad\left\|A^{-1/2}-B^{-1/2}\right\|_2&\leq\frac{1}{2}\{\max(\|A\|_2,\|B\|_2)\}^{1/2}\|A^{-1}\|_2\|B^{-1}\|_2\|A-B\|_2.\end{aligned}\qquad(7.23)$$

From the upper and lower bounds of the eigenvalues of $\omega(x;b)$ and the equivalence between the Euclidean norm $\|\cdot\|$ and the spectral norm $\|\cdot\|_2$, deduce that for any h_i,b_i, $i=1,2$,

$$\|\omega^{-1/2}(x-uh_1;b_1)-\omega^{-1/2}(x-uh_2;b_2)\|\leq C\|\omega(x-uh_1;b_1)-\omega(x-uh_2;b_2)\|.$$

for some constant C. Finally, apply the definition of the Euclidean property. $\square$

In what follows, $\bar{\omega}(x;b)=\int_{\mathbb{R}^q}\omega(x-bv)L(v)\,dv$, D is a domain that can be written as $\{x:p(x)\geq0\}$ for some real polynomial $p(x)$, or finite unions and/or intersections of such sets.

Lemma 7.8. *If $\omega(x)$ has eigenvalues uniformly bounded away from zero and infinity on D and is Hölder continuous on D (i) $\bar{\omega}(x;b)$ has eigenvalues uniformly bounded away from zero and infinity on D if $L(\cdot)$ is strictly positive in a neighborhood of the origin; (ii) $\{(x,u)\mapsto\bar{\omega}(x-hu;b):h,b\in[0,h_0]\}$ is Euclidean entrywise for a constant envelope.*

Proof. Part (i) is straightforward, Part (ii) is shown as follows. Since $\omega(x)$ is positive definite, there exists a unique lower triangular matrix $T(x)$ with positive diagonal entries such that $\omega(x) = T(x)T'(x)$. The eigenvalues of $\omega(\cdot)$ are uniformly bounded away from zero and infinity iff the same holds for the eigenvalues of $T(\cdot)$, that is its diagonal entries. Moreover, the entries of $T(\cdot)$ are Hölder continuous functions with exponent a since they obtain recursively from the entries of $\omega(\cdot)$ through the equations

$$T_{i,i}^2(x) = \omega_{i,i}(x) - \sum_{k=1}^{i-1} T_{i,k}^2(x),\ T_{i,j}(x) = T_{j,j}^{-1}(x)\left(\omega_{i,j}(x) - \sum_{k=1}^{j-1} T_{i,k}(x)T_{j,k}(x)\right),\ 1 \leq i \leq r,\ i > j\,.$$

By Theorem 3.3 and Remark 3.4 of Le Gruyer and Archer (1998), each entry $T_{i,j}(x)$ can be extended to $\mathbb{R}^q$ such that its extension is Hölder continuous with the same exponent and remains between $\inf_{x\in D} T_{i,j}(x)$ and $\sup_{x\in D} T_{i,j}(x)$. The lower triangular matrix extension $\tilde{T}(\cdot)$ yields an extension $\tilde{\omega}(\cdot) = \tilde{T}(\cdot)\tilde{T}'(\cdot)$ of $\omega(\cdot)$ on $\mathbb{R}^q$ which is positive definite with eigenvalues uniformly bounded away from zero and infinity and Hölder continuous. By Lemma 2.13 of Pakes and Pollard (1989) and the fact that multiplication preserves Euclideanity, deduce that the class of functions $(x, u, v) \mapsto \widetilde{\omega}(x - uh - vb)\mathbb{I}(x - hu - vb \in D) = \omega(x - uh - vb)$, $x, u, v \in \mathbb{R}^q$, $h, b \in [0, h_0]$, is Euclidean for a constant envelope. The result follows since Euclideanity is preserved by integration. □

The two above lemma can be combined to yield a result on $\bar{\omega}^{-1/2}(x - uh; b)$.

Lemma 7.9. *$\{(x, u) \mapsto \bar{\omega}^{-s}(x - hu; b)\mathbb{I}\,(x - hu \in D) : h, b \in [0, h_0]\}$, $s = 1/2$ or 1, is Euclidean for a constant envelope under the assumptions of Lemma 7.8.*

Proof. Lemma 7.6 and the fact that Euclideanity is preserved by addition yield that the class of functions $\{(x, u) \mapsto \widetilde{\bar{\omega}}(x - uh; b) = \mathbb{I}(x - hu \in D^c)I + \bar{\omega}(x - hu; b) : h, b \in [0, h_0]\}$ is Euclidean for a constant envelope. By definition, the eigenvalues of $\widetilde{\bar{\omega}}(x - uh; b)$ stay away from zero and infinity and $\widetilde{\bar{\omega}}(x - uh; b) = \bar{\omega}(x - uh; b)$ whenever $x - uh \in D$.
By Lemma 7.7, the class $\left\{(x, u) \mapsto \widetilde{\bar{\omega}}^{-1/2}(x - uh; b) : h, b \in [0, h_0]\right\}$ is then Euclidean for a constant envelope, and by Lemma 7.6-(i), so is the class $\left\{(x, u) \mapsto \widetilde{\bar{\omega}}^{-1/2}(x - uh; b)\mathbb{I}(x - hu \in D) : h, b \in [0, h_0]\right\}$. A similar reasonning applies when $s = 1$. □

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Table 1: Results for Dominguez and Lobato's setup

	$n=50$			$n=200$		
Estimator	h	Ratio RMSE	Ratio MAE	h	Ratio RMSE	Ratio MAE
			$X \sim N(0,1)$			
NLS		0.0504	0.0390		0.0236	0.0186
DL		2.3590	2.2527		2.4795	2.4181
SMD	1	1.2828	1.2858	1	1.2626	1.2590
SMD	0.3	1.3298	1.3332	0.3	1.3110	1.3101
Eff. SMD	0.3	1.2160	1.2057	0.3	1.0952	1.0895
			$X \sim N(1,1)$			
NLS		0.0226	0.0178		0.0109	0.0087
DL		2.1284	2.1362		2.2066	2.2157
SMD	1	1.2348	1.2363	1	1.2257	1.2313
SMD	0.3	1.2513	1.2522	0.3	1.2274	1.2319
Eff. SMD	0.3	1.1353	1.1299	0.3	1.0581	1.0603

The levels of RMSE and MAE, not their ratio, are reported for NLS.

Table 2: Results for Kitamura and al.'s setup

	$n=50$			$n=200$		
Estimator	h	Ratio RMSE	Ratio MAE	h	Ratio RMSE	Ratio MAE
GLS		0.1342	0.1066		0.0657	0.0523
		0.1623	0.1285		0.0795	0.0632
FGLS		1.2757	1.2345		1.3037	1.3944
		1.4323	1.3854		1.2347	1.3397
SEL	.3049	1.4266	1.3241	.2310	1.2894	1.1589
		1.2938	1.2279		1.1797	1.1077
	.7622	1.3015	1.2056	.5776	1.1608	1.0359
		1.1886	1.1522		1.0982	1.0917
	1.2195	1.3681	1.2166	.9242	1.1561	1.1047
		1.2170	1.1574		1.0940	1.1035
Eff. SMD	.3049	1.1660	1.1627	.2310	1.0967	1.0914
		1.2077	1.2073		1.1190	1.1150
	.7622	1.2968	1.2829	.5776	1.2128	1.2143
		1.2159	1.2070		1.1552	1.1524
	1.2195	1.4417	1.4338	.9242	1.3449	1.3499
		1.2719	1.2645		1.2170	1.2162

The levels of RMSE and MAE, not their ratio, are reported for GLS.

Table 3: Rejection percentages of bootstrap test

	$n = 50$			$n = 100$		
	h	5% level	10% level	h	5% level	10% level
Model (5.9) $X \sim N(0,1)$ $H_0: \theta_0 = 5/4$						
NLS		10.3	16.3		7.0	13.0
SMD	1	4.4	11.8	1	4.8	10.4
	.3	5.0	12.0	.3	5.0	9.4
Model (5.9) $X \sim N(1,1)$ $H_0: \theta_0 = 5/4$						
NLS		8.1	14.3		6.2	11.7
SMD	1	7.0	13.8	1	5.4	11.0
	.3	8.0	13.4	.3	5.6	10.2
Model (5.10) $H_0: \beta_2 = 1$						
FGLS		29.2	35.6		20.7	27.6
Eff. SMD	.3049	6.8	12.6	.2654	4.6	9.2
	.7622	9.8	15.2	.6635	6.2	11.2
	1.2195	11.8	18.6	1.0616	7.8	12.4